NATIONAL BUREAU OF STANDARDS REPORT

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DEVELOPMENT OF A HIGH-INTENSITY STANDARD OF TOTAL AND SPECTRAL IRRADIANCE

Final Report to the
National Aeronautics and Space Administration
Order Number C-14588-B

NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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[2] Located at Boulder, Colorado 80302.
[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

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DEVELOPMENT OF A HIGH-INTENSITY STANDARD OF TOTAL AND SPECTRAL IRRADIANCE

by

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I. INTRODUCTION

The establishment of a high-intensity irradiance standard capable of producing irradiances of at least one solar constant (about 136 mw cm^{-2}) at a practical working distance required an extensive evaluation of both commercially available and NBS designed sources. This report describes the development of a suitable source and the subsequent calibration of the selected source in terms of total and spectral irradiance.

II. EVALUATION OF HIGH INTENSITY SOURCES

1.0 Commercially Available Sources

A study was made of a number of commercially available sources evaluating them in terms of (1) reproducibility, (2) stability, (3) spectral quality, and (4) capability of producing total irradiance on the order of at least one solar constant at a practical working distance.

Previous experience [1,2] with high pressure arc lamps such as Hg, Hg-Xe, Xe, and Krypton indicated that although sufficient energy was available, the reproducibility and long term stability of these units did not meet the requirements necessary for use as a radiometric standard.

Consideration was also given to 5000-watt tungsten filament projection lamps. These lamps were satisfactory with respect to reproducibility; however, the stability of these units over a period of 15 hours was relatively poor. Also, the large size of the envelope and the rather short distances required to produce sufficient irradiances caused serious difficulties in alignment. Another detrimental characteristic of the 5000-watt lamp was the glass envelope. Glass does not transmit below about 3500 Å; thus, the spectral quality in the near ultra-violet was quite poor.

2.0 NBS Designed Source

The survey of commercially available sources indicated that in order to obtain a reasonable stable irradiance on the order of a solar constant, the NBS would be required to design a source which would meet the necessary requirements. Preliminary measurements and calculations made on a 1000-watt Sylvania tungsten coiled-coil filament lamp mounted in a ceramic reflector were very promising. Several different parabolically shaped aluminum forms were constructed and coated with a high, diffusely reflecting material such as MgO, $BaSO_4$, CaF_2 or Al_2O_3. 1000-watt tungsten-halogen type lamps were then mounted in the reflectors. These units produced relatively high irradiances; however, the time required for the unit to come to equilibrium was about 30 minutes - far too long for use as a standard.

Emphasis was then given to the General Electric clear and frosted 1000-watt tungsten halogen lamps when mounted in specially designed slip-cast fused silica reflectors. It was found that positioning the lamps within the housing too close to the back wall of the reflector resulted in a very short life for the lamps (less than 5 hours). The design of the reflector was accordingly modified a number of times until an operating period of more than 150 hours was obtained. The lamp mounted in the reflector is shown in Figure 1. The effective size of the radiating area is only 3.2 cm by 5 cm. The presence of the reflector increases the radiant flux in a direction normal to the front surface of the unit by a factor of about 3. The combination of a small radiating area and the increased flux due to the reflector results in a source capable of producing at least 136 mw cm^{-2} at a reasonable working distance of 40 cm.

3.0 Stability Tests - Instrumentation

The experimental apparatus used to determine both the total and the spectral stability of these units is shown in Figure 2. In order to efficiently cover the full spectral range of 0.25 μm to 2.5 μm, at least two photoelectric detectors are required. An RCA 935 phototube was chosen to cover the ultra-violet and visible ranges and an Eastman Kodak PbS cell was selected to cover the near infrared region. The two detectors were mounted to an adjustable table within a special dual-detector housing so that by means of a vernier drive; either detector could be positioned directly behind the entrance port of the housing. Provisions were made to place narrow band-pass interference filters directly over the entrance port. Thus, through the selection of a number of interference filters and the two detectors, a simple spectroradiometer was constructed which was capable of making discrete spectral measurements over the wavelength region of 0.25 to 2.5 μm. For the total radiation measurements, a thermopile without a cover window was employed as the detector.

Both the thermopile and the detector housing were mounted on an optical bench. The source to be evaluated and a reference lamp were set up in a manner that allowed each of the sources to alternately be in alignment with one of the detectors. By noting the position of the detector on the optical bench, it was possible to accurately realign either the thermopile or the entrance aperture of the detector housing with either of the lamps. The test source was operated continuously whereas the reference lamp was turned on only during the measurements. A 33 Hz chopper was mounted on the optical bench in front of the detector housing. The output signal from each photoelectric detector was then syncronously amplified and subsequently displayed on a digital voltmeter as was the thermoelectric output of the thermopile after first being amplified by a nanovoltmeter.

The measurement procedure was as follows:

(1) With the 935 phototube in position and an appropriate filter in place, the detector's output was recorded when alternately aligned with the test and reference sources. This was successively done for each of the ultra-violet and visible filters.

(2) The PbS cell was then positioned behind the entrance aperture and readings were taken for each of the sources with the infrared filters in place.

(3) The thermopile's output was then recorded when irradiated by each of the sources.

(4) The reference lamp was turned off; the test source continued to operate.

The above steps were repeated about every 10 - 15 hours until either the test source failed or sufficient information was available to enable evaluation of the data.

The reference source consisted of a clear 1000-watt tungsten halogen lamp. These lamps were previously found to be stable for periods of 50 hours or more. By taking the ratios* for the total

*Relative spectral or total detector output when irradiated by test source vs output when irradiated by reference source.

and the various spectral wavelengths, it was possible to detect any relative change that might occur with the test source.

In order to expedite the stability studies, a second system was constructed. This system was identical in principle to the first with the exception of the means of spectral isolation. In this case, for obtaining discrete spectral energy bands, a quartz double-prism monochromator was employed rather than interference filters. The monochromator was mounted on a second optical bench along with a second thermopile. Thus, two systems, operating simultaneously, were available for studying the stability properties of various high intensity sources.

4.0 Stability Test - Results

Initial tests on the 1000-watt tungsten halogen lamp - ceramic reflector conbination indicated that ultra-violet degradation of the fused silica reflective coating was occurring. Although these lamps are not overly "rich" in ultra-violet radiation, their close proximity to the reflecting surface (about 6 mm) enhanced the amount of ultra-violet energy incident upon the reflector. Table 1 gives the results for a typical 1000-watt tungsten lamp when mounted in a ceramic reflector having a fused silica reflecting surface. Note that in the ultra-violet region at 0.27 μm, the change in ratios over a 40 hour interval is 13 percent and that with increasing wavelength, the change in ratios decreases. At the longer wavelength of 2.5 μm the change over 40 hours operation decreased to 2%, and the change in the total irradiance of the source is also about 2% - too large a change to be considered for use as a radiometric standard.

Various diffusely reflecting materials such as $BaSO_4$, MgO, CaF_2, Al_2O_3, and a new Eastman Kodak white paint were then applied to the ceramic reflectors and subsequently evaluated for long term stability. Of those materials, the units coated with Al_2O_3 proved to be the most stable. The greatest change occurred during the first 24 hours. Table 2 gives the results for a clear 1000-watt tungsten halogen lamp mounted in a ceramic reflector with a flame sprayed Al_2O_3 coating. During the first 25 hours the change in ultra-violet irradiance at 2537 Å is 6%, however, very little change occurred between 25 and 117 hours. The total irradiance remained fairly constant over the entire 117 hour period of operation and the standard deviation of the total (or thermopile) ratios between 25 and 117 is only 0.27%. It should be noted that the total amount of ultra-violet irradiance below 0.4 μm is only about 0.2% of the total radiation from the source. Thus, a few percent change in the ultra-violet irradiance has an insignificant effect on the total irradiance. However, since the source is to be used as a standard of both total and spectral irradiance, it is desirable that the spectral radiometric output remain fairly constant for a reasonable length of time (at least 20 hours).

In Table 3 data is given for a frosted 1000-watt lamp - Al_2O_3 coated reflector combination. In this case, data were only taken after the unit had been seasoned* for a period of 25 hours. The decrease in the ultra-violet irradiance during the period 25 hours to 135 hours is only 2 1/2 %. The visible, near infrared, and total ratios are fairly constant. The standard deviation of the total ratios is only 0.2% which is the limitation in instrumental repeatibility.

Tests were conducted on a number of these units, each employing either clear or frosted lamps, the results of which were similar to those shown in Tables 2 and 3. Thus, by mounting the General Electric clear or frosted tungsten halogen lamp in a flame sprayed Al_2O_3 coated ceramic reflector and seasoning the unit for 25 hours, a source was developed which, over a period of at least 50 hours, remained stable with respect to total irradiance to within 0.2% and to within one or two percent for spectral irradiances.

III. TOTAL IRRADIANCE CALIBRATIONS

The establishment of the high intensity sources as standards of total irradiance was accomplished by comparing the irradiance of a group of lamp-reflector units to the irradiance of a blackbody as defined by the Stefan-Boltzmann radiation law. The accuracy and precision with which a total radiation calibration of this type can be performed is dependent upon a number of parameters such as: (1) the quality of the blackbody; (2) the temperature

*Seasoned or operated at rated voltage for a specified period of time.

measurement and temperature uniformity of the blackbody; (3) the ability to determine the amount of blackbody energy which is absorbed by the atmosphere; (4) the quality of the total radiation detectors; (5) the resolution and precision with which the detector's output can be recorded; (6) the ability to repeatedly supply a known amount of electrical power to the high intensity source; (7) the ability and accuracy with which the high intensity source can be attenuated; (8) the accuracy to which the area and temperature of the blackbody limiting aperture is known; and (9) the ability to accurately align and measure distances between certain components in the system.

1.0 Evaluation of NBS Blackbody

The quality of a "blackbody" is a function of the effective emissivity of the cavity opening and the temperature uniformity of the cavity enclosure. Once these two parameters have been determined, the radiance (either total or spectral), can be computed using the appropriate radiation equations provided that the temperature of the enclosure is known. The blackbody employed was constructed of a cylindrical casting of an alloy of 80% nickel and 20% chromium. The overall length is 15.2 cm., the outside diameter is 7.6 cm., and the wall thickness is 1.27 cm. Two openings are provided; one larger radiation aperture (1.6 cm. diameter) and a smaller opening (0.4 cm. diameter) into which a temperature sensor could be inserted. In order to increase the emissivity and diffuseness of the enclosure, the back wall of the cylinder was machine grooved at a slight angle of about 10°.

Before actual use, the enclosure was placed in an oven and heated in air to 1400°K for more than 100 hours. The subsequent oxidizing of the metal resulted in a surface having a relatively low reflectance. Figure 3 shows the infrared spectral reflectance of a sample of the oxidized metal when heated to a temperature of 1273°K. The reflectance of the sample was measured on a Cary-White 90 Infrared Spectrophotometer by the Spectrophotometry and Colorimetry Section at NBS. Using an average value of 0.1* for the wall reflectance a value of 0.9 was obtained for the emissivity of the interior surface of the enclosure. Thus, from the geometrical dimensions of the enclosure, the emissivity of the material, and Gouffé's equation [3], a calculated effective emissivity for the cylindrical enclosure of 0.999 was obtained.

The temperature of the blackbody was both measured and controlled by the voltage generated by a platinum-platinum (10% rhodium) thermocouple. The thermocouple ice point was maintained at 0.0 ± 0.05°C by means of a commercial thermoelectric ice point. Copper wires without soldered connections carried the thermocouple voltage to copper knife switches, by which it could be directed - alternately or simultaneously - to the temperature measuring or temperature controlling equipment.

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*It was not possible with the apparatus available to obtain values below 2.5 μm, but since at the temperature of 1273°K about 65% of the flux is above 2.5 μm and 99% is above 1.2 μm, it was felt that this was not a serious limitation.

The temperature measuring equipment consisted of a Leeds & Northrup K-3 potentiometer which was calibrated by the NBS Electrical Instrument Section, a Leeds & Northrup electronic null indicator, and a standard reference cell calibrated by the NBS Electrochemistry Section.

Temperature controlling equipment consisted of a Leeds & Northrup 10877 control system plus an FAG 3 magnetic amplifier. The 10877 control system includes a No. 10810 set point unit, a No. 9834-2 null detector, and a No. 10877 CAT (current adjusting type) control unit.

The mode of operation was as follows:

(1) The desired blackbody temperature was selected, and the corresponding thermocouple voltage was set into the set point unit by means of a 0 - 50 mV coarse adjustment with 5 mV steps and a ten-turn helipot fine adjustment that divided each 5 mV interval into one thousand 5 µV divisions. The output of the set point unit was the difference-thermocouple voltage minus set point voltage. This output formed the input for the null detector, which amplified it; the output of the null detector was the input for the CAT unit, which transformed it to a current source; finally, the output of the CAT unit was the input for the FAG 3 magnetic amplifier. The magnetic amplifier provided up to a 20 A current at up to 90 V in order to heat the blackbody oven.

(2) To operate the blackbody at 1400°K, for instance, the oven current was set manually at about 15 A when the oven was

started from room temperature. When the null detector indicated the blackbody temperature was roughly 50 degrees below the desired temperature, the CAT unit was switched from manual to automatic control. As the blackbody temperature approached the desired value, the sensitivity of the null detector was slowly increased to a level sufficient to maintain the equilibrium temperature.

(3) If the equilibrium temperature differed from the set point, it could be corrected by a minor adjustment of the set point.

The precision temperature controller coupled with the high heat capacity of the associated blackbody furnace (which gives the blackbody good thermal stabilities) enabled the blackbody temperature to be repeated from one day to the next to within ± 0.5 degrees at about 1400°K. The short term stability was about ± 0.2 degrees.

The thermocouple was calibrated by the NBS Temperature Section and had a corresponding uncertainty of ± 0.5°K on the International Practical Temperature Scale (IPTS). The correction required because of conduction losses in the thermocouple, obtained by surrounding the thermocouple assembly with a heater guard where it emerged from the blackbody, was found to be 0.25°K. Agreement between the corrected thermocouple reading and a carefully calibrated optical pyrometer measurement was 0.1°K. To check for depreciation of the thermocouple, replacement or recalibration of the element was required from time to time.

Temperature uniformity of the opening of the blackbody was established by means of an optical pyrometer and thermocouple. The opening was scanned both vertically and horizontally with a visual optical pyrometer and found to be uniform to about 1°K which was the limitation of the sensitivity of these particular observations. A secondary check of temperature uniformity was made by placing the thermocouple at different positions along the rear wall of the cylinder. These measurements revealed that the temperature gradient along the back surface of the blackbody was less than 0.3 degrees.

2.0 Atmospheric Absorption

The radiant energy emitted by the blackbody reaches the radiation detector only after traversing the atmosphere for a certain distance. The absorption of radiation at certain wavelengths by atmospheric constituents such as carbon dioxide, water vapor, and ozone is so intense that their effect on the transmitted radiation should be taken into account when extrapolating back from the measured radiation to the true target radiation. Most of this absorption occurs in the infrared region of the electromagnetic spectrum [4]. Although the blackbody - detector distance was relatively short (about 30 cm.), an atmospheric absorption correction was considered essential since more than 99% of the radiation emitted by a 1400°K blackbody is in the infrared.

The spectral transmittance through an absorbing path of length χ is given by Lambert's law [5]:

$$T_\lambda = e^{-k_\lambda \chi}$$

where T_λ is the transmittance at wavelength λ and k_λ is the absorption coefficient at wavelength λ. However, since accurate absorption coefficients throughout the entire wavelength region of interest are not available, the effect of atmospheric absorption was determined experimentally.

These measurements were made by placing a cylindrical stainless steel tube 30 cm. in length and 7.5 cm. in diameter between the limiting aperture of the blackbody and the radiation detector (see Figure 4). Each end of the tube had a 2 cm. diameter circular opening. Over each opening, a KBr window was vacuum mounted by means of a press and "O" ring. Two baffles were provided inside the tube to reduce scattered light. The tube was fitted with a pressure valve; thus the tube could be evacuated to a pressure of 10^{-5} mm. KBr was chosen for the window material since it has a uniform transmittance from the visible out to about 22 μm; the spectral region which embraces 99.5% of the radiation from a 1400°K blackbody. The spectral transmittance of KBr was measured on a Cary-14 spectrophotometer over the spectral region of 0.3 to 2.5 μm and on a Beckman IR-9 Infrared Spectrophotometer from 2.5 to 25 μm.

Irradiance measurements were taken when the tube was evacuated to a pressure of 10^{-5} mm. The pressure valve was then released and irradiance measurements were taken at atmospheric pressure. The ratio of the detector outputs at atmospheric and at 10^{-5} mm pressure conditions is then an indication of the attenuation of a 1400°K blackbody irradiance at 30 cm. due to atmospheric absorption. This procedure was repeated a total of 14 times over a period of a few days. Both the room temperature and the relative humidity were recorded during each set of measurements.

The results of the measurements along with the mean and the standard deviation are given in Table 4. Thus, in order to correct for atmospheric absorption, the calculated blackbody irradiance was multiplied by 0.9841.

An analysis was made to determine if a correction should be applied to the above measurements due to the difference in the index of refraction of air and of a vacuum. For the vacuum measurements, radiation is traversing an [air-KBr-vacuum-KBr-air] path whereas in the second case, the path consists of [air-KBr-air-KBr-air]. The indices of refraction for air, vacuum, and KBr are 1.00029 [6], 1.0, and 1.53 [7] respectively. The reflection ρ_{12} at the interface of two mediums is given as:

$$\rho_{12} = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \qquad (5.2)$$

where n is the index of refraction and the subscripts 1 and 2 denote mediums 1 and 2.

Designating air, KBr, and vacuum as mediums 1, 2, and 3 respectively, the reflection R of one KBr window for the vacuum situation to a close approximation is:

$$R_v \cong \rho_{12} + \frac{\rho_{23}(1-\rho_{12})-(1-\rho_{21})}{1-\rho_{21}\rho_{23}} \tag{5.3}$$

and, for the measurement at atmospheric pressure, the reflection R_a of one KBr window is approximately:

$$R_a = \rho_{12} + \frac{\rho_{21}(1-\rho_{12})(1-\rho_{21})}{1-\rho_{21}^2} \tag{5.4}$$

Calculations of the combined reflection of the two windows for each condition of measurement resulted in a reflection difference of less than 0.01%. Thus, the data in Table 4 were not adjusted.

3.0 Evaluation of Total Radiation Detector

Most sources of thermal radiation emit energy over a wide spectral range. A 1400°K blackbody emits more than 60 percent of its energy on the long wavelength side of 2.5 μm, whereas the tungsten lamp-ceramic reflector unit emits most of its energy on the short wavelength side of 2.5 μm. Thus, when using a radiation detector as a transfer device, it is essential that the detector be equally sensitive to radiant energy over an extremely wide wavelength region. The type of sensor most commonly used as a "black" radiation detector is the thermopile. However, recent investigations [8, 9, 10] have revealed that the responsivities of these detectors are not necessarily constant with wavelength.

A close approach to a spectrally "flat" detector is the cavity or "blackbody" detector which was designed at NBS and built by the Charles M. Reeder Co. One of these units is shown in Figure 5. The unit is constructed in the form of a cone (20% angle) and coated with gold black. To reduce the heat capacity and thereby decrease the response time, the cone is made of 2 μm thick gold foil. Along the outside fold of the foil, several wires are attached which serve as supporting members and thermojunction connectors.

The effective absorption of the conical receiver can be approximately calculated using Gouffé's equation; however, the spectral reflectance of gold black varies considerably from one specimen to another - depending on the method of deposition [11]. Therefore, the spectral uniformity of the detector was determined experimentally by comparison to a thermopile heavily coated with Parson's Black Paint. The reflectance of Parson's Black Paint has been found to be constant from the visible out to about 20 μm to about ± 1% [12].

The spectral comparison was made by placing both detectors in a metal housing which in turn was mounted on an optical bench. The mechanical means for mounting the detectors was such that both detectors were at the same height and same distance from the front face of the housing. The housing, when mounted on the optical bench, could be moved either horizontally with respect to the source or toward or away from it. The micrometer settings on the optical bench enabled the repositioning of the housing and the detectors within to be very precise. Isolated spectral bands spaced at approximately equal intervals from 0.75 μm to

20 μm were obtained through the combination of about 30 narrow bandpass interference filters and various radiating sources. The filters were mounted in a fixed position between the detector and the source. Each of the thermopile leads was connected to a double pole-double throw switch. The switch was then connected to a Keithley Nanovoltmeter and the output signals finally displayed on a strip-chart recorder. It was then possible to alternately place each detector in position and uniformly irradiate its receiver. When this method of comparison was used it was possible to repeat response ratios to about one percent. Figure 6 shows the results of the comparison. From this figure it can be seen that the cavity detector is "flat" over the wavelength region of interest.

The stability of the cavity detector was checked by irradiating the receiver with a stable carbon filament lamp. When comparing the irradiance from the high intensity source to that of the blackbody the detector was only used as a transfer device; therefore, only short term stability was required. The results of these measurements indicated that the responsivity of the cavity detector was constant to within the ability to take measurements, i.e., to within ± 0.2% for 30 minute periods.

A rough check of the detector's sensitivity was made by placing the detector about 30 cm. from the 1400°K blackbody. The sensitivity was roughly 0.6 volts per watt or the level of the output signal was normally on the order of 20 μv[illegible] Thus, the cavity detector fulfilled the desired requirements of spectral uniformity, short term stability and sensitivity.

4.0 Method for Obtaining Equivalent Flux

When the irradiance of the blackbody was compared to that of the high intensity unit, a large difference existed between the irradiance of the two sources. These differences ranged up to a couple orders of magnitude, depending on which blackbody aperture was used. Therefore, either a linearity check of the detector system, or some means of accurately attenuating the more intense source to a value roughly equivalent to that of the other source was necessary.

In this case, it was found both convenient and accurate to use sector disks as a means of both performing linearity checks and as a means for obtaining equivalent irradiances.

Available for use were sets of sector disks calibrated by the Length Measurement Section at NBS. The nominal transmittance of these disks, together with their measured transmittances and uncertainties are given in Table 5.

5.0 Instrumental Apparatus

The experimental setup for determining the total irradiance of the high intensity source is shown in Figure 7. The blackbody and associated oven were mounted on an optical bench which was capable of moving in two mutually perpendicular directions. A 6 inch I-beam, 7 feet in length, was positioned normal to the front face of the blackbody and served as a rigid support to which other components were mounted. A double water-cooled shield-aperture holder and shutter were mounted to the I-beam directly in front of the blackbody opening. The cavity detector was fastened to a specially constructed rotating platform which provided movement in the lateral, longitudinal, and vertical directions. The high intensity source, a water cooled shield and shutter, and the sector disk were also placed on platforms which in turn were mounted to the I-beam.

Alignment of the blackbody aperture and the cavity detector was achieved by inserting a 30.025 cm. rod through the blackbody aperture (see Figure 8). The various adjustments of the detector platform enabled the limiting aperture of the detector to be positioned normal to and at a known distance from the blackbody aperture. Once the detector was properly aligned, the rod was removed and the blackbody and oven were repositioned behind the limiting aperture.

The high intensity source was aligned with the detector by placing a specially constructed straight edge, either 40 cm. or 100 cm. in length directly against the front face of the detector (see Figure 9). The source was then positioned flush with the square end of the straight edge. A water cooled shield having a 4 inch diameter opening was placed 15 cm. from the source. Attached to the shield was a water cooled shutter. The sector disk was placed about 10 cm. from the cavity detector. A black back-drop was placed about 1 meter behind the high intensity source.

The operating power for the lamp was produced by a bank of batteries capable of supplying 140 volts at about 30 amperes. The electrical control and measurement system is shown in Figure 10. The lamp was wired in series with a set of variable rheostats, the batteries, and a 15 ampere shunt. The voltage across the shunt was measured with a Leeds & Northrup K-3 Potentiometer. An electronic zero center micro voltmeter served as a null indicator. The standard cell, potentiometer, and shunt were all calibrated by the Electricity Division at NBS.

The thermoelectric output of the cavity detector was amplified by a Keithley model 148 nanovoltmeter and read out on an NLS model X-1 digital voltmeter.

The blackbody apertures consisted of a set of six stainless steel disks with circular knife-edge openings. The disks were machine threaded and could be screwed into the water-cooled aperture holder. The nominal diameters of the apertures were 1, 2, 4, 6, 8, and 10 mm. The actual diameters were measured at 30 degree intervals by the NBS Length Section. Table 6 gives the diameters for each aperture along with the means and the standard deviation.

6.0 Measurement Procedure and Results

With the instrumentation set up as shown in Figure 7, and after the blackbody had achieved temperature equilibrium (about 4 hours after turning on the oven); the temperature of the room, shutters and shields; the relative humidity and EMF of the Pt. - Pt. 10 Rh thermocouple were recorded. The previously aligned lamp-reflector unit was turned on (at a current of 8.300 amperes d.c.) and allowed to warm up for 15 minutes. A series of ten readings were taken with the detector facing toward the blackbody. The detector was then rotated 180 degrees and an equal number of measurements were taken on the high intensity source. In order to detect any drift or change that might have occurred during the course of the measurements, a second set of ten readings were taken for both sources.

The above procedure was followed for each of eight lamp-reflector units at a distance of 100 cm. During these measurements, the blackbody remained at essentially the same temperature and the same limiting aperture was employed. Once a set of measurements was completed, either the blackbody temperature or the limiting aperture was changed. The eight units were again compared to the blackbody. This was done at least three times for each of the eight sources. The blackbody temperature ranged from about 1370 to 1400 °K and either the 4, 6, or 8 mm diameter aperture was used; most of the measurements were made with the 6 mm aperture. The blackbody-detector distance was always kept at 30.025 cm. and the 10% sector disk was placed between the cavity detector and the high intensity source.

The total irradiance in watts/cm^2 of the blackbody E_{BB} at the limiting aperture of the detector was calculated from the following equation:

$$E_{BB} = \frac{\varepsilon_0 \alpha \sigma r^2 \, (T_{BB}{}^4 - T_S{}^4)}{d^2}$$

where, ε_0 = Effective emissivity of blackbody (0.9991),

α = Atmospheric absorption correction (0.9841),

σ = Stefan-Boltzmann constant (5.6697×10^{-12} watt/K^4-cm^2),

r = Radius of blackbody aperture (cm),

d = Blackbody-detector distance (30.025 cm.),

T_{BB} = Temperature (Thermodynamic Kelvin Temperature Scale, TKTS) of blackbody (K),

and T_S = Temperature (TKTS) of blackbody shutter (K).

Table 7 gives the calculated blackbody irradiances in mw-cm^{-2} for 0.1 degree intervals from 1374 to 1378 °K and from 1392 to 1400 °K when the diameter of the blackbody aperture was 6 mm.

The total irradiance of a lamp-reflector unit E_S was then obtained from the relationship:

$$E_S = \frac{E_{BB} \cdot \overline{D}_S}{T \cdot \overline{D}_{BB}}$$

where, E_{BB} = Blackbody irradiance (watt/cm^2),

$\overline{D}_S$ = Mean of ten detector outputs when irradiated by high intensity source (volts),

$\overline{D}_{BB}$ = Mean of ten detector outputs when irradiated by blackbody (volts), and T = Transmittance of sector disk.

The results of the measurements made at 100 cm. are given in Table 8. Note that the irradiance for each unit is about 23 mw cm^{-2}; a factor of about 6 less than one solar constant.

As previously mentioned, these units produce on the order of one solar constant irradiances at a distance of 40 cm. However, the energy difference between the lamp-reflector unit and the blackbody is a factor of about 100. Thus, in order to attenuate the high intensity source to a value roughly equivalent to that of the blackbody, a 1% sector disk would be required. Since the accuracy of the 1% transmitting sector disk was not as well defined as the higher transmitting disks (see Table 5), the measurements at 40 cm. were taken relative to the calibrated irradiance at 100 cm. This was done using the experimental set up shown in Figure 11. The cavity detector was mounted on an optical bench and could easily be shifted from 100 to 40 cm. from the lamp-reflector unit. The 20% transmitting sector disk was only turned on when the detector-source distance was 40 cm. Since, fairly high irradiances were being measured, the repeatibility in separate sets of measurements was extremely good (about ±0.1%). The ratio of the irradiances at 40 and 100 cm. for each trial run along with the mean for each unit is given in Table 9. The irradiance at 40 cm. was then determined by multiplying the irradiance at 100 cm. by the corresponding mean ratio. The final values are shown in Table 10.

As a check on the total irradiance of one high intensity unit a secondary method was employed wherein a quartz plate calibrated for spectral transmittance was interposed between the blackbody and the detector. Thus, the problems which arise due to H_2O and CO_2 absorption beyond 4 μm, possible non-spectral uniformity of the detector beyond 4 μm, and non-planckian radiation of the blackbody beyond 4 μm are eliminated. However, the uncertainty of the spectral transmittance of the quartz plate was about ± 0.5%. Figure 12 illustrates the relative spectral irradiance of a blackbody operated at 1300°K, the spectral irradiance from a 300°K blackbody (the temperature of the water cooled shutter which may be considered zero on this scale), the spectral transmittance of the quartz plate, and the water vapor absorption for the path length between the blackbody aperture and the detector. The water vapor absorption on the short wavelength side of 4 μm was calculated on the amount equivalent to 0.0001 percipitable cm. of water at normal temperature and pressure and is based on data published by Wyatt et al. [13]. The CO_2 values are based upon the data by Stull et al. [14]. The combined absorptions amounted to approximately 0.5%. The water vapor content of the atmosphere was determined from measurements of the temperature and relative humidity of the laboratory during the course of the measurements (which ranged around 75°F and 70%) and from the curves shown in Figure 13. These curves were prepared from the Smithsonian metrological tables [13] and give the density of water vapor at saturation as a function of temperature;

the moisture content (the absolute humidity of the atmosphere) was determined in grams per cubic meter.

The total transmitted blackbody irradiance E_{BB} was then determined from the following equation:

$$E_{BB} = \frac{0.995\ A}{d^2}\left[\int_{\lambda_1}^{\lambda_2} L_{BB}(\lambda)\tau(\lambda)\ d\lambda - \int_{\lambda_1}^{\lambda_2} L_S(\lambda)\tau(\lambda)d\lambda\right]$$

where, 0.995 = correction due to atmospheric absorption,

A = Area of blackbody aperture (cm^2),

d = Blackbody aperture-detector distances (cm.),

$\tau(\lambda)$ = Spectral transmittance of quartz plate,

L_{BB} = Spectral radiance of blackbody (watt $ster^{-1}$ cm^{-3}),

L_S = Spectral radiance of 300°K shutter (watt $ster^{-1}$ cm^{-3}),

and the limits of integration λ_1 and λ_2 are the transmittance cutoff wavelengths of the quartz plate.

The results of this measurement agreed with the mean value obtained with the primary method to 0.4%.

A check was also made on the uniformity of the irradiance at 40 cm. This was done by moving the detector first vertically and then horizontally at 2 mm increments and noting the associated detector output for each position. These measurements indicated that the total irradiance was uniform to about ± 0.3% over a 2 cm. by 2 cm. area.

IV. SPECTRAL IRRADIANCE CALIBRATIONS

The methods presently employed at the NBS for measuring the spectral irradiances of various sources over the solar spectrum (about 0.25 to 2.5 μm) consist of comparing the spectral irradiance of the source under investigation with that of an NBS standard of spectral irradiance. Two spectroradiometers, one based on a conventional prism monochromator and the other on a system employing narrow band-pass interference filters, were set up and used in the spectral calibrations. The eight high intensity units previously calibrated for total irradiance were all compared to NBS irradiance standards using the prism method; only two of these units were calibrated on both sets of equipment.

1.0 Prism Spectroradiometric Instrumentation

As shown in Figure 14, the basic component of the conventional spectroradiometer is the quartz double-prism monochromator. The use of a double-prism instrument reduces the scattered flux to a minimum and also offers a relatively high degree of resolution. The monochromator is light in weight and compact, such that it can be mounted on a rotary turntable. Thus, the instrument can be rotated to view either the standard of spectral irradiance or the high intensity unit. The use of Infrasil quartz prisms allows the monochromator to be used over the entire wavelength range of interest (0.30 to 2.5 μm).

The wavelength calibration of the monochromator was accomplished through the use of known emission lines of various arc lamps and by calibrated narrow band-pass interference filters.

Since most radiant energy detectors vary considerable in sensitivity over their receiving surface [2, 9] and the transmittance of monochromators vary over their optical aperture, an averaging sphere was placed at the entrance slit of the monochromator. This ensured that the detector always viewed the same "source", i.e. a certain area of the sphere wall. The sphere, which was 7.6 cm. in diameter, had a circular entrance port (14 mm in diameter) and a rectangular (19 mm x 6.35 mm) exit port. The entrance port was situated far enough off the normal to the exit port such that it could not be seen directly by the detector. A number of sphere coatings were examined for relative efficiency with the resultant use of MgO reagent grade powder.

Two detectors were employed to cover the spectral range from 0.3 μm to 2.5 μm. An EMI S-20 response photomultiplier, mounted in a coolable (193°K) housing, was used from 0.3 to 0.8 μm, and a 2 mm by 10 mm PbS cell (also cooled to 193°K) was used from about 0.65 μm to 2.5 μm. The incident flux was chopped at 33 Hz and the output of the lock-in amplifier was fed to a digital voltmeter (DVM).

To reduce the effect of stray radiation, a cylindrical shield (11.4 cm. in length and 11.4 cm. in diameter) with a flat black interior was mounted to the averaging sphere directly in front of the entrance aperture. The front end of the shield was removeable and, depending on the geometry involved, a diaphragm having the appropriate size opening was used. In all cases, care was taken that the limiting aperture of the system was the entrance port of the averaging sphere.

When comparing the spectral irradiance of the standard to that of the high intensity source, differences in energy of up to 5 existed between the two sources. Therefore, the more intense source had to be attenuated to a value roughly equivalent to that of the standard. It was found both convenient and accurate to use a neutral density screen (which had a uniform transmittance of 20.7 percent) as a means for obtaining equivalent irradiances. The transmittance of the screen was determined through the use of the calibrated sector disks and with the screen positioned exactly as used in the irradiance measurements i.e. placed directly over the opening of the cylindrical shield.

2.0 Prism Spectroradiometric Measurements

When measurements were made with the prism instrument, the standard of spectral irradiance was aligned normal to and at a distance of 50 cm. from the entrance port of the averaging sphere. The spectrometer, along with its auxiliary components, was then rotated to a pre-set position and the high intensity source was aligned at a distance of 40 cm. Since the spectral irradiance standards also operated at 8.30 amperes, both sources were wired in series. Thus, current control was not critical since small errors in this measurement would cancel.

Comparisons of irradiances were made at 30 wavelengths spaced between 0.30 μm and 2.5 μm. Each high-intensity unit was calibrated relative to at least three standards. The defining equation for determining the spectral irradiance E_λ at wavelength λ (nm) is given as:

$$E_\lambda = E_{\lambda_s} V/V_s \ t$$

where, E_{λ_s} = Spectral irradiance of standard ($\mu W\ cm^{-2}\ nm^{-1}$)

V = DVM voltage reading for high intensity source

V_s = DVM voltage reading for standard

t = Transmittance of attenuating screen.

The spectral irradiances for the eight lamp-reflector units are given in Table 11. A comparison of irradiance values for a lamp-reflector combination and a typical 1000-watt standard of spectral irradiance is shown in Figure 15. Note that at the longer wavelengths the lamp-reflector unit is a factor of 5 times more intense whereas at 300 nm only a factor of 2 exists. This can be attributed to the low reflectance of the Al_2O_3 coating in the ultra-violet.

3.0 Filter Spectroradiometric Instrumentation

The photoelectric filter spectroradiometer (see Figure 16) consists of a set of 36 narrow band-pass interference filters mounted at 10 degree intervals on an aluminum disk. The disk can be rotated by a 36-position servometer to any one of the set positions. A spring cam arrangement ensures that each filter can be positioned directly in front of the detector.

In order to eliminate stray radiation, the entire system was enclosed in a light-tight box. Again, to facilitate comparison of the two sources, the system was mounted on an optical bench that allowed a rapid interchange between the sources.

The electronics employed with the filter set up, along with the readout system, radiation shield, and attenuating screen were interchangeable with the prism spectroradiometer. However, a duplicate chopper was required since the chopper itself was an integral part of both systems.

4.0 Filter Spectroradiometric Measurements

As with the prism instrument, measurements with the filter set up were made with the standard at 50 cm. and the high-intensity source at 40 cm. The spectral irradiances of two high-intensity units as determined with both sets of instrumentation are shown in Figures 17 and 18. In both cases, the solid lines illustrate the spectral irradiance values as determined with the prism spectroradiometer and the circles are representative of the spectral irradiances as determined with the filter spectroradiometer. The results of both methods are the average of two or more sets of measurements. The agreement between the two methods is better than $\pm$ 1% over most of the spectral range.

V. ACCURACY AND PRECISION

The parameters influencing the accuracy and precision with which sources of thermal radiation can be calibrated in terms of total irradiance were mentioned in Section II. When setting up the 1000-watt lamp-reflector units as high intensity standards of total irradiance, care was taken that the uncertainties contributed by these factors were kept to a minimum.

The degree to which the radiation from any cavity enclosure actually conforms to the Planck equation is not easily determined. For these measurements experimental verification of the total blackbody radiation was somewhat achieved when a quartz window was placed over the blackbody aperture. This method, however, had an uncertainty of ± 0.5% in the transmittance of the quartz window. From a theoretical approach, the quality of the radiator should be better than ± 0.1%; the value subsequently used in the error analysis computations.

The measurement of the blackbody temperature through the use of a calibrated Pt. - Pt. .10 Rh thermocouple was determined to ± 0.5 degrees on the International Practical Temperature Scale (IPTS). However, in order to obtain the best blackbody radiance values, the thermocouple calibration was corrected to the Thermodynamic Kelvin Temperature Scale (TKTS). This requires an addition of 1.4 degrees to the IPTS temperature. The standard deviation uncertainty of the correction has been estimated to be ± 0.25 degrees. These uncertainties in the blackbody temperature produce uncertainties of ± 0.15% and ± 0.075%, respectively, in the radiation values. The

K-3 potentiometer, which was used to measure the EMF of the thermocouple, has a calibration accuracy better than 1 μv. Since a 12 μv difference in thermocouple output corresponds to a 1 degree change in temperature, the error associated with the thermocouple EMF measurements amounted to less than ± 0.05%.

The lengths of the 30.025 cm. rod and the two straight edges were measured by the NBS machine shop to within ± 0.1 mm. In the case of the balckbody, this corresponded to an uncertainty in irradiance of ± 0.07%. For the high-intensity source set at the two distances, an error of ± 0.1 mm contributed less than 0.05% uncertainty in the calibration values. The area of the blackbody aperture produced an uncertainty of ± 0.15%.

The correction factor due to atmospheric absorption was primarily dependent on the precision of the measurements. Thus, the standard deviation for this correction factor was ± 0.1%.

The uncertainty in the calibration introduced by an error in the setting of the lamp current was determined by taking total irradiance measurements for two different currents. The results are shown in Figure 19. The lamp-reflector unit was allowed to warm-up at 8.300 amperes for 16 minutes after which a series of 8 irradiance measurements were taken. The current was then reduced 0.1000 ampere and 7 sets of measurements were made. Finally, the current was reset to 8.300 amperes and another set of data was taken. Two minute intervals separated each of 21 sets of measurements.

The results show that the total irradiance drops 3.7% for a reduction in current from 8.300 to 8.200 amperes. The K-3 potentiometer and shunt box (which were calibrated by the NBS Electrical Instrument Section(could set the current to better than 0.0001 amperes. Thus, the error associated with the current setting is less than ± 0.004%.

The uncertainty in the attenuation of the high-intensity source, as shown in Table 5, is ± 0.1% for the 10% transmitting disk and ± 0.04% for the 20% disk; these were the two disks employed in most of the measurements.

The precision with which the total irradiance values repeated from one measurement set to another was calculated on the basis of a standard deviation for each of the eight sources. This ranged from about ± 0.2% to ± 0.4% and had a mean standard deviation of 0.3%.

The sources of error associated with the total irradiance calibrations are summarized in Table 12. Adding these errors in quadrature, a final uncertainty for the assigned total irradiance values of ± 0.9% at the 2 - σ level was obtained.

An error analysis for the spectral irradiance measurements was fairly straight forward. The standards to which the high-intensity units were compared have uncertainties ranging from 6 - 7 % at a wavelength of 300 nm to about 3 - 4 % in the visible and infrared. As previously mentioned, each high-intensity unit was compared to at least two standards of spectral irradiance. The difference between the two comparisons was generally less than 1%. The errors associated with measurement of distance and setting of current were less than ± 0.5%. Thus, based on the previously assigned values for the 1000-watt standards of spectral irradiance, the high-intensity standards have associated uncertainties which range from about 8% at 300 nm to 5% throughout the remainder of the calibrated region.

VI. CONCLUDING REMARKS

In general, the high-intensity standards of total and spectral irradiance can be used to calibrate radiometers and spectroradiometers in terms of responsivity where high irradiances are required. Some of the more prominent scientific disciplines involved with such measurements include aerospace (primarily solar simulation), meterology, air pollutions, and various defense orientated applications.

When these standards are used to calibrate thermal detectors for response to total irradiance, care should be taken that the detector is uniform in response from the near ultra-violet through the medium infrared. If a window is used with the radiometer, an appropriate transmittance correction must be applied. This correction factor, however, can and usually will vary depending on the window employed and the source to be measured. For example, a quartz window may have a transmittance of 87% for the total irradiance from the standard even though its spectral transmittance is about 92% through the near ultra-violet, visible, and near infrared regions. For another source, a low temperature heater or blackbody for example, the total transmittance of the quartz will be significantly lower depending on the temperature of the source. Similarly, a CaF_2 window (having a uniform transmittance from the near ultra-violet to about 7 μm) may have a total transmittance for the standard source of 91%, and as with the quartz window, a low transmittance for a low temperature source. However, in this case, the relative difference in transmittances for the two sources is not as great as with the quartz window.

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LIST OF TABLES

TABLE 1

Relative Spectral and Total Irradiance Ratios for a Clear 1000-Watt Lamp in a Silica Coated Reflector at 150 cm. VS. a 1000-Watt Reference Source at 75 cm. as a Function of Time

Time (hrs.) λ(μm)	0	6	10	17	35	40
.270	1.13	1.11	1.09	1.08	1.04	1.00
.300	1.20	1.17	1.15	1.13	1.08	1.05
.350	1.31	1.28	1.26	1.25	1.19	1.17
.400	1.54	1.50	1.48	1.47	1.40	1.38
.500	1.81	1.77	1.75	1.74	1.67	1.65
.550	1.88	1.85	1.84	1.83	1.76	1.74
.600	1.94	1.91	1.90	1.90	1.83	1.82
.700	2.02	2.00	2.00	1.99	1.95	1.94
.750	2.04	2.02	2.03	2.03	1.99	1.98
1.0	2.05	2.05	2.05	2.05	2.02	2.02
1.5	2.05	2.08	2.08	2.08	2.07	2.07
2.0	2.08	2.10	2.09	2.09	2.08	2.08
2.5	2.16	2.16	2.14	2.16	2.12	2.12
TOTAL	1.981	1.961	1.974	1.964	1.955	1.939

TABLE 2

Relative Spectral and Total Irradiance Ratios for a Clear 1000-Watt Lamp in an Al_2O_3 Coated Reflector at 150 cm. VS. a 1000-Watt Reference Source at 75 cm. as a Function of Time

Time (hrs.) / λ (μm)	2	6	25	31	54	61	82	87	110	117
.2537	.950	.930	.893	.899	.903	.898	.906	.905	.914	.910
.300	.930	.903	.869	.870	.870	.871	.875	.875	.874	.877
.500	1.53	1.52	1.50	1.50	1.50	1.50	1.51	1.51	1.50	1.51
.700	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.62	1.61	1.62
1.00	1.60	1.60	1.61	1.60	1.62	1.63	1.62	1.61	1.62	1.63
1.50	1.61	1.62	1.63	1.62	1.64	1.65	1.64	1.64	1.64	1.65
TOTAL	1.627	1.631	1.635	1.633	1.644	1.645	1.636	1.640	1.639	1.643

Standard Deviation of the TOTAL from 25 - 117 hrs. = 0.27%

TABLE 3

Relative Spectral and Total Irradiance Ratios for a Frosted 1000-Watt Lamp in an Al_2O_3 Coated Reflector at 150 cm. VS. a 1000-Watt Reference Source at 75 cm. as a Function of Time

Time (hrs.) / λ(μm)	25	47	72	80	104	127	135
.270	.591	.582	.578	.579	.571	.576	.581
.300	.696	.685	.680	.678	.675	.677	.682
.350	.884	.873	.870	.867	.863	.863	.868
.400	1.15	1.13	1.13	1.13	1.13	1.13	1.13
.500	1.52	1.51	1.51	1.51	1.51	1.51	1.52
.550	1.60	1.60	1.60	1.60	1.60	1.60	1.61
.600	1.69	1.69	1.69	1.68	1.69	1.69	1.69
.700	1.76	1.76	1.75	1.76	1.76	1.76	1.77
.750	1.79	1.79	1.78	1.79	1.79	1.80	1.80
1.0	1.82	1.83	1.82	1.82	1.83	1.83	1.84
1.5	1.87	1.88	1.88	1.88	1.90	1.90	1.90
2.0	1.89	1.89	1.90	1.89	1.92	1.91	1.92
2.5	1.88	1.89	1.90	1.90	1.92	1.91	1.92
TOTAL	1.720	1.720	1.723	1.718	1.725	1.727	1.725

Standard Deviation of the TOTAL from 25 - 135 hrs. = 0.20%

TABLE 4

Results of Atmospheric Absorption Measurements

Trial No.	Correction Factor
1	0.9851
2	.9832
3	.9826
4	.9831
5	.9845
6	.9839
7	.9851
8	.9858
9	.9863
10	.9832
11	.9842
12	.9836
13	.9836
14	.9831

$m = 0.9841$

$\sigma = 0.1\%$

TABLE 5

Transmittance and Uncertainties of Sector Disks

Nominal Transmittance	Measured Transmittance	Uncertainty (Percent of T)
0.80	0.7999	≤ 0.01
.70	.7001	< .01
.60	.5991	< .01
.50	.4999	< .01
.40	.3993	.01
.30	.3002	.02
.20	.2002	.02
.10	.09988	.05
.05	.05003	.10
.01	.00977	.50

TABLE 6

Diameters of Blackbody Apertures

Orientation (Degrees)	Diameter (mm)	Mean (mm)	σ (% of mean)
0	1.0742		
30	1.0745	1.0740	.062%
60	1.0742		
90	1.0730		
0	2.0647		
30	2.0618	2.0637	.062%
60	2.0641		
90	2.0641		
0	4.0237		
30	4.0281	4.0249	.058%
60	4.0250		
90	4.0228		
0	6.0159		
30	6.0226	6.0160	.043%
60	6.0163		
90	6.0090		
0	8.0449		
30	8.0420	8.0428	.025%
60	8.0440		
90	8.0404		
0	10.0660		
30	10.0745	10.0701	.035%
60	10.0704		
90	10.0694		

TABLE 7

Blackbody Irradiance at 30.025 cm. as a Function of Temperature

(Aperture Diameter = 6.016 mm)

Temp. (K)	E (mw cm^{-2})	Temp. (K)	E (mw cm^{-2})	Temp. (K)	E (mw cm^{-2})
1374.0	1.9878	1392.0	2.0942	1396.0	2.1185
1374.1	1.9883	1392.1	2.0948	1396.1	2.1191
1374.2	1.9889	1392.2	2.0954	1396.2	2.1197
1374.3	1.9895	1392.3	2.0960	1396.3	2.1203
1374.4	1.9901	1392.4	2.0966	1396.4	2.1209
1374.5	1.9907	1392.5	2.0972	1396.5	2.1215
1374.6	1.9912	1392.6	2.0979	1396.6	2.1221
1374.7	1.9918	1392.7	2.0984	1396.7	2.1227
1374.8	1.9924	1392.8	2.0990	1396.8	2.1233
1374.9	1.9930	1392.9	2.0997	1396.9	2.1239
1375.0	1.9936	1393.0	2.1002	1397.0	2.1245
1375.1	1.9941	1393.1	2.1009	1397.1	2.1252
1375.2	1.9947	1393.2	2.1015	1397.2	2.1258
1375.3	1.9953	1393.3	2.1021	1397.3	2.1264
1375.4	1.9959	1393.4	2.1027	1397.4	2.1270
1375.5	1.9965	1393.5	2.1033	1397.5	2.1276
1375.6	1.9971	1393.6	2.1039	1397.6	2.1282
1375.7	1.9976	1393.7	2.1045	1397.7	2.1288
1375.8	1.9982	1393.8	2.1051	1397.8	2.1294
1375.9	1.9988	1393.9	2.1057	1397.9	2.1300
1376.0	1.9994	1394.0	2.1063	1398.0	2.1307
1376.1	1.9999	1394.1	2.1069	1398.1	2.1313
1376.2	2.0005	1394.2	2.1075	1398.2	2.1319
1376.3	2.0011	1394.3	2.1081	1398.3	2.1325
1376.4	2.0017	1394.4	2.1087	1398.4	2.1331
1376.5	2.0023	1394.5	2.1093	1398.5	2.1337
1376.6	2.0029	1394.6	2.1100	1398.6	2.1343
1376.7	2.0035	1394.7	2.1106	1398.7	2.1349
1376.8	2.0040	1394.8	2.1112	1398.8	2.1355
1376.9	2.0046	1394.9	2.1118	1398.9	2.1362
1377.0	2.0052	1395.0	2.1124	1399.0	2.1368
1377.1	2.0058	1395.1	2.1130	1399.1	2.1374
1377.2	2.0064	1395.2	2.1136	1399.2	2.1380
1377.3	2.0070	1395.3	2.1142	1399.3	2.1386
1377.4	2.0076	1395.4	2.1148	1399.4	2.1392
1377.5	2.0081	1395.5	2.1154	1399.5	2.1398
1377.6	2.0087	1395.6	2.1160	1399.6	2.1404
1377.7	2.0093	1395.7	2.1166	1399.7	2.1411
1377.8	2.0099	1395.8	2.1172	1399.8	2.1417
1377.9	2.0105	1395.9	2.1178	1399.9	2.1423
1378.0	2.0111	1396.0	2.1185	1400.0	2.1429

TABLE 8

Total Irradiances of High-Intensity Units in mw cm^{-2}

at a Distance of 100 cm.

	Total Irradiances				
Unit No.	1	2	3	4	Mean
T-1	24.15	24.07	24.17	24.17	24.14
T-3	23.31	23.42	23.38	23.29	23.35
T-4	24.77	24.77	24.70		24.75
T-5	23.87	23.95	23.91		23.91
T-6	22.79	22.85	22.92	23.03	22.90
T-7	22.78	22.85	22.80	22.94	22.84
T-8	22.07	22.17	22.22	22.25	22.18
T-9	22.98	23.01	23.03		23.00

TABLE 9

Ratio of Total Irradiances (40 cm. / 100 cm.) for High-Intensity Units

	Ratios				
Unit No.	1	2	3	4	Mean
T-1	6.041	6.034	6.020	6.032	6.032
T-3	6.045	6.045	6.028	6.039	6.039
T-4	6.038	6.016			6.027
T-5	6.020	6.016			6.018
T-6	6.057	6.053	6.041	6.050	6.050
T-7	6.062	6.062	6.039	6.054	6.054
T-8	6.054	6.047	6.033	6.045	6.045
T-9	6.028	6.029			6.028

TABLE 10

Total Irradiance of High-Intensity Units

in mw cm^{-2} at a Distance of 40 cm.

Unit No.	Total Irradiance
T-1	145.6 mw-cm^{-2}
T-3	141.0
T-4	149.2
T-5	143.9
T-6	138.5
T-7	138.3
T-8	134.1
T-9	138.6

TABLE 11

Spectral Irradiance of High-Intensity Units in

$\mu W\ cm^{-2}$-nm^{-1} at 40 cm. when Operated at 8.30 Amperes

λ,μm	T-1	T-3	T-4	T-5	T-6	T-7	T-8	T-9
.300	0.414	0.406	0.383	0.387	0.469	0.457	0.433	0.485
.320	0.835	0.821	0.788	0.789	0.945	0.920	0.871	0.967
.350	2.15	2.10	2.05	2.04	2.37	2.32	2.19	2.42
.370	3.58	3.49	3.42	3.39	3.88	3.81	3.60	3.96
.400	7.16	6.95	6.87	6.76	7.53	7.49	7.06	7.70
.450	16.6	15.9	16.0	15.6	16.8	16.9	15.9	17.1
.500	30.3	29.3	29.8	29.0	30.1	30.3	28.8	30.5
.550	45.5	43.9	45.4	44.0	44.6	45.1	42.9	45.2
.600	61.2	58.6	61.3	59.3	59.2	60.0	56.9	59.9
.650	76.6	73.0	76.5	74.2	73.2	74.2	70.5	74.1
.700	90.2	85.7	89.5	87.2	85.1	86.3	81.9	86.2
.750	99.7	94.5	99.0	96.3	93.5	94.7	90.1	95.0
.800	105	99.8	105	102	98.5	99.7	95.0	100
.900	109	104	110	107	102	103	98.4	104
1.000	108	102	108	105	99.1	101	96.0	101
1.100	102	95.8	102	98.5	92.6	94.5	90.2	94.6
1.200	93.6	88.0	93.8	90.8	84.7	86.5	82.7	86.8
1.300	84.6	79.9	85.1	82.4	76.9	78.5	75.0	78.4
1.400	75.8	71.8	76.5	74.1	69.3	70.6	67.5	70.2
1.500	67.5	63.9	68.1	65.9	62.0	62.9	60.1	62.3
1.600	59.5	56.3	60.1	58.1	55.1	55.8	53.2	54.9
1.700	52.0	49.4	52.6	50.8	48.6	49.0	46.8	48.0
1.800	45.2	43.1	46.0	44.3	42.5	42.7	41.0	41.7
1.900	39.3	37.5	39.9	38.5	37.0	37.1	35.7	36.2
2.000	34.0	32.6	34.7	33.4	32.3	32.2	31.2	31.5
2.100	29.8	28.6	30.4	29.3	28.4	28.2	27.5	27.7
2.200	26.4	25.4	27.0	26.0	25.3	25.0	24.4	24.6
2.300	23.6	22.8	24.3	23.3	22.9	22.5	22.0	22.1
2.400	21.4	20.7	22.1	21.2	20.9	20.5	20.0	20.1
2.500	19.6	19.1	20.3	19.5	19.3	18.9	18.5	18.5

TABLE 12

Summary of Errors in Total Irradiance Measurements

Source of Error	Percentage
Measurement of blackbody temperature on IPTS	± 0.15
Conversion of temperature to TKTS	.075
Measurement of thermocouple EMF	.05
Quality of blackbody	.1
Distance Measurement (blackbody)	.07
Distance Measurement (high-intensity unit)	.05
Area of blackbody aperture	.15
Atmospheric absorption	.1
Sector disk calibration	.1
Setting of current	.004
Precision	.3

LIST OF ILLUSTRATIONS

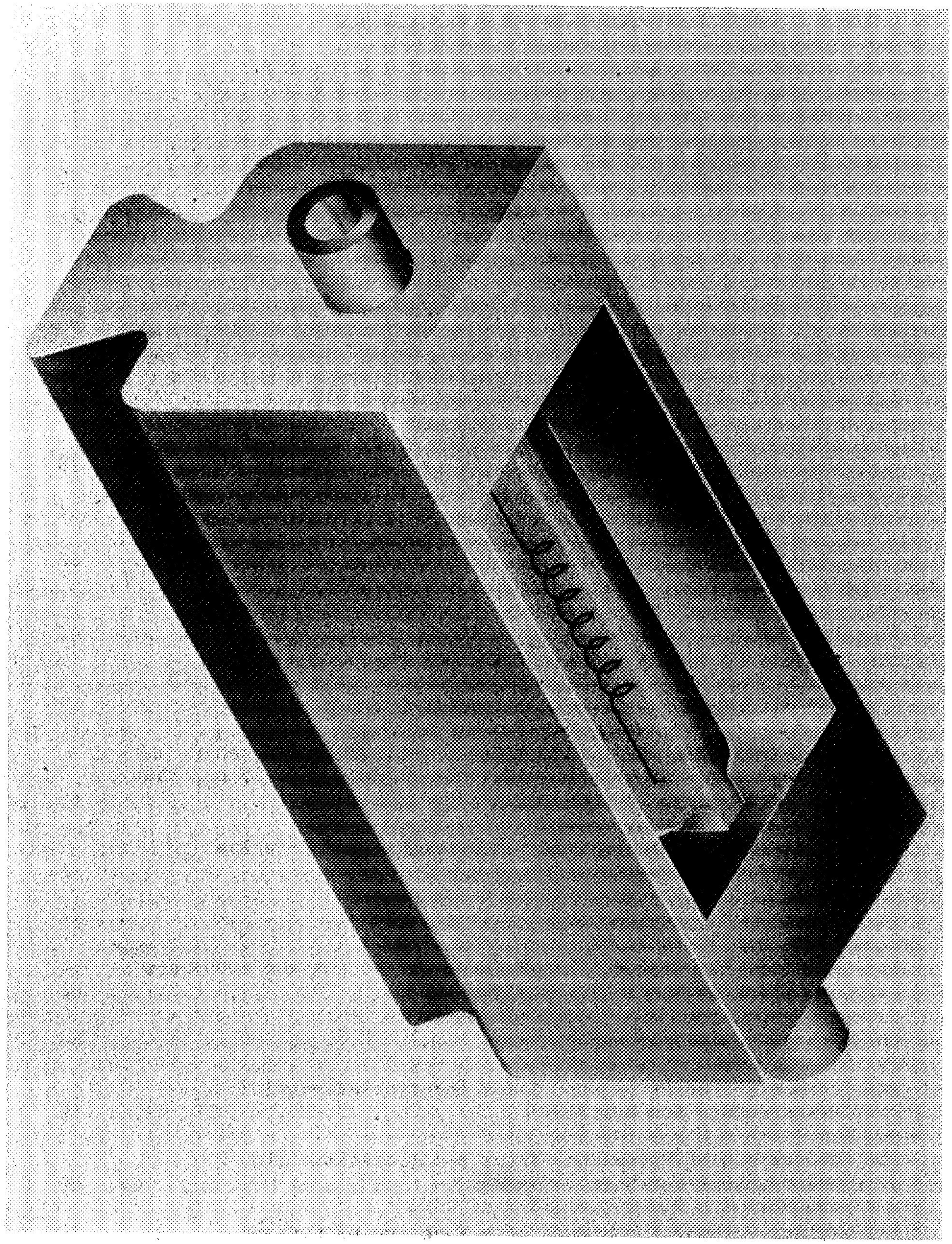


Figure 1

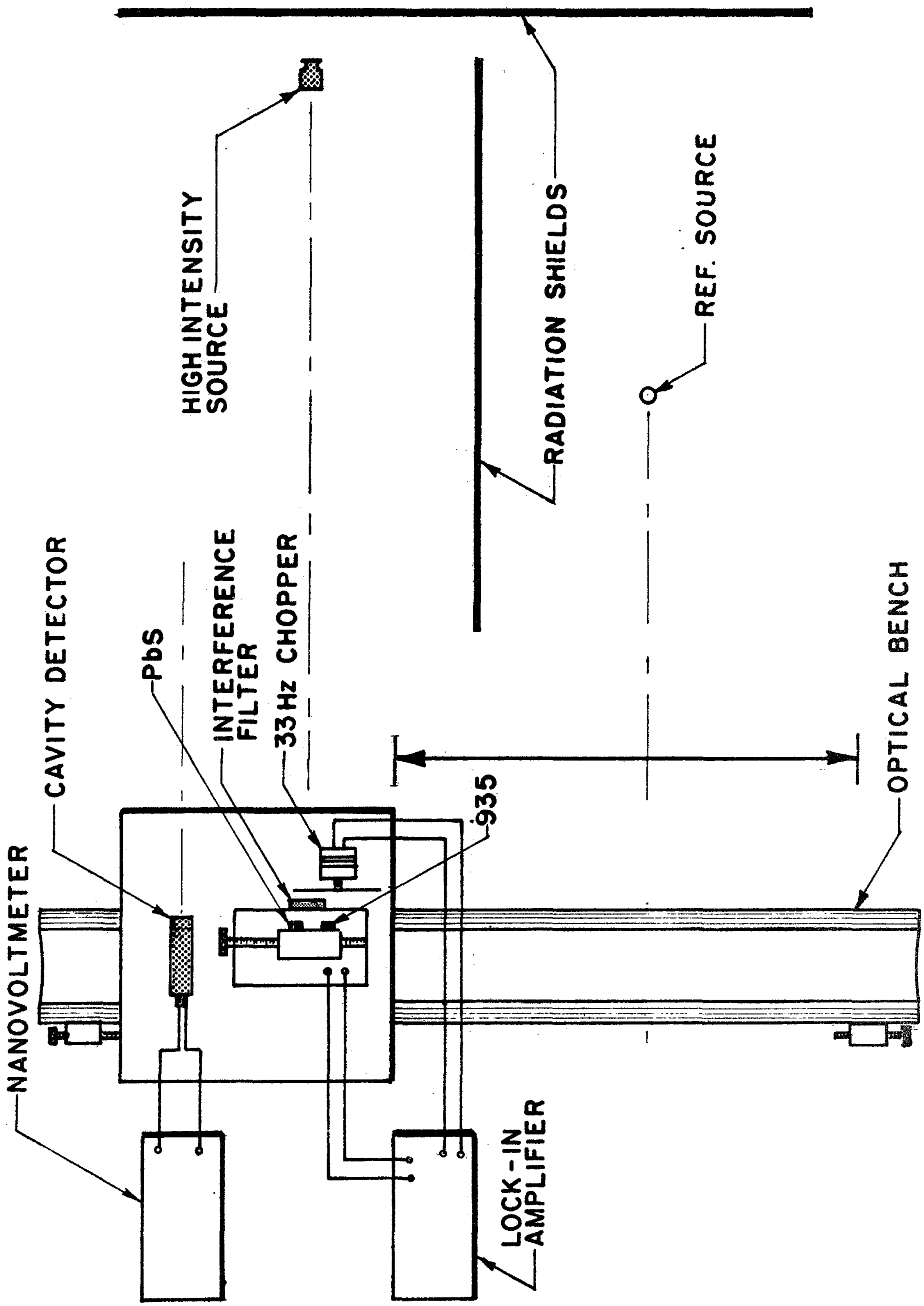

NANOVOLTMETER
CAVITY DETECTOR
PbS
INTERFERENCE FILTER
33 Hz CHOPPER
HIGH INTENSITY SOURCE
RADIATION SHIELDS
REF. SOURCE
935
OPTICAL BENCH
LOCK-IN AMPLIFIER

Figure 2

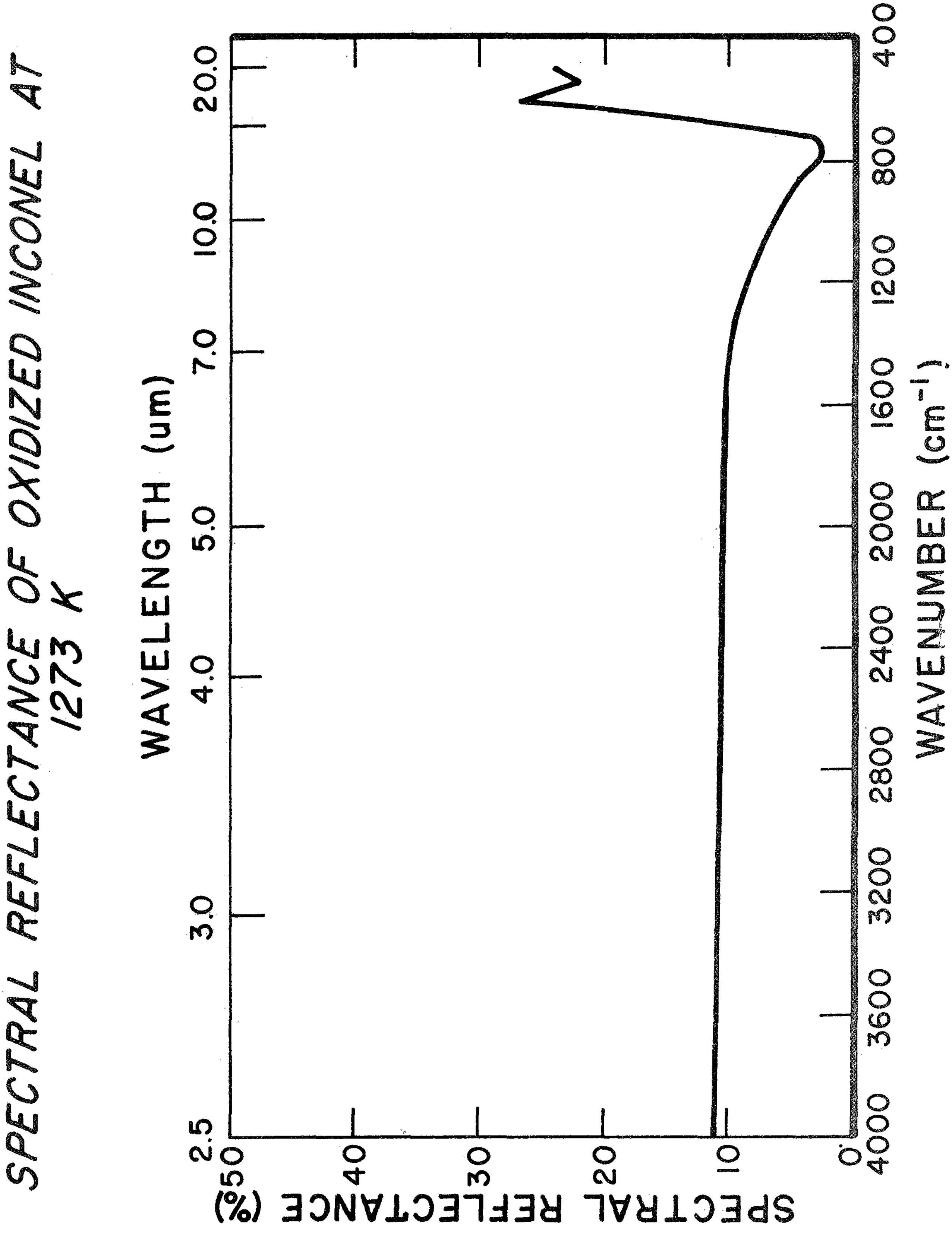

SPECTRAL REFLECTANCE OF OXIDIZED INCONEL AT 1273 K
WAVELENGTH (um)
2.5
3.0
4.0
5.0
7.0
10.0
20.0
SPECTRAL REFLECTANCE (%)
50
40
30
20
10
0
WAVENUMBER (cm⁻¹)
4000
3600
3200
2800
2400
2000
1600
1200
800
400

Figure 3

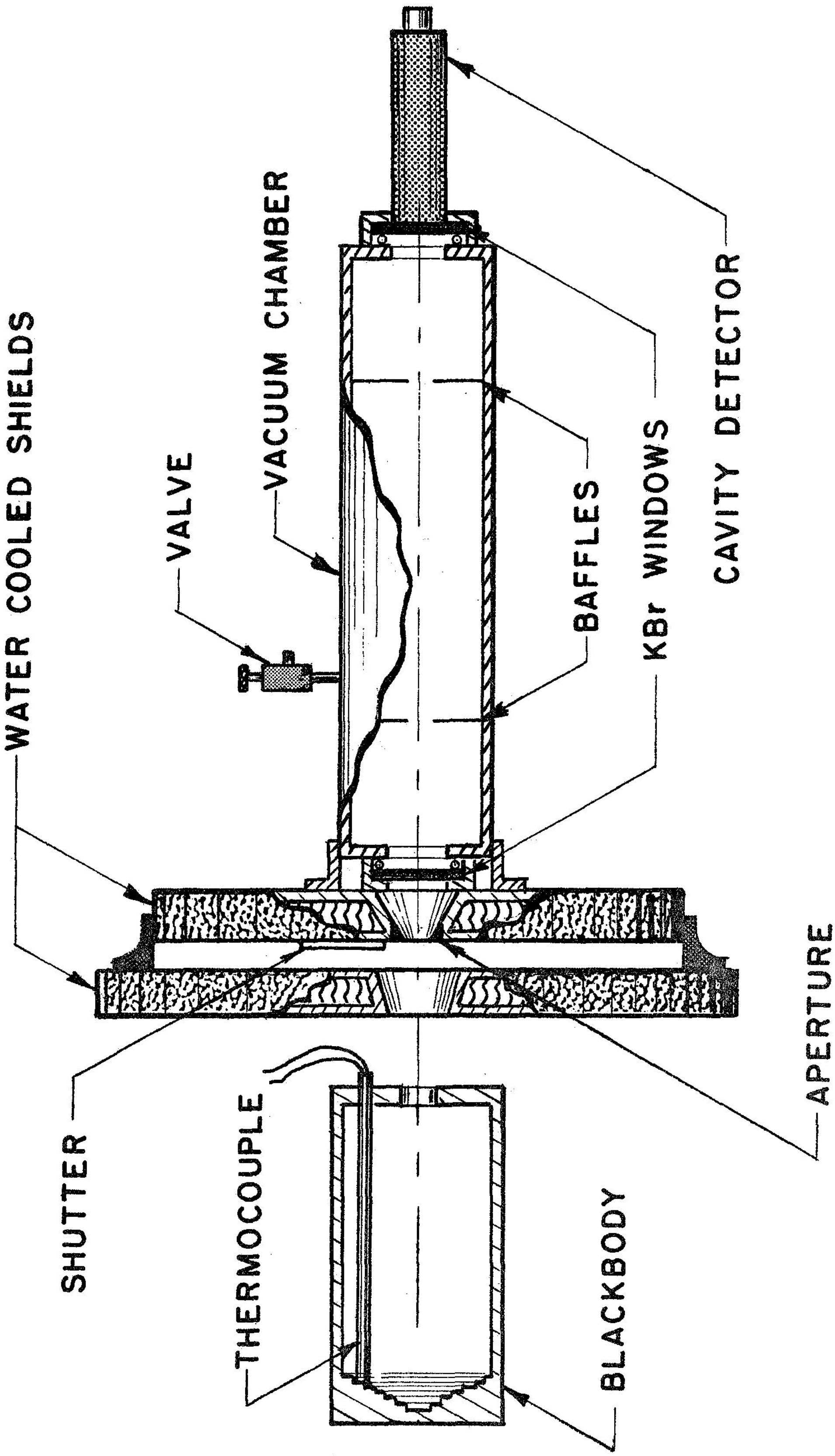

WATER COOLED SHIELDS
VALVE
VACUUM CHAMBER
BAFFLES
KBr WINDOWS
CAVITY DETECTOR
APERTURE
SHUTTER
THERMOCOUPLE
BLACKBODY

Figure 4

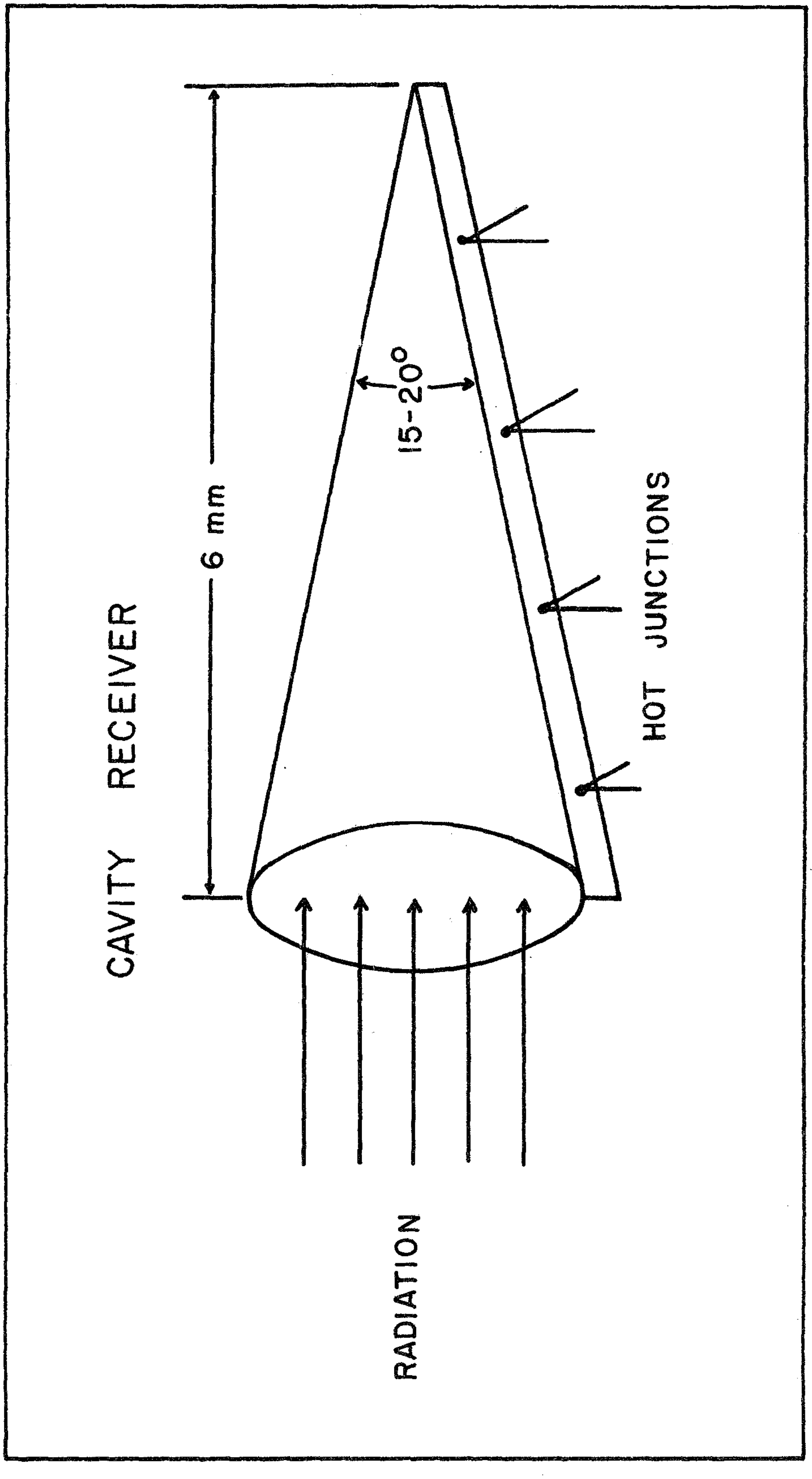


Figure 5

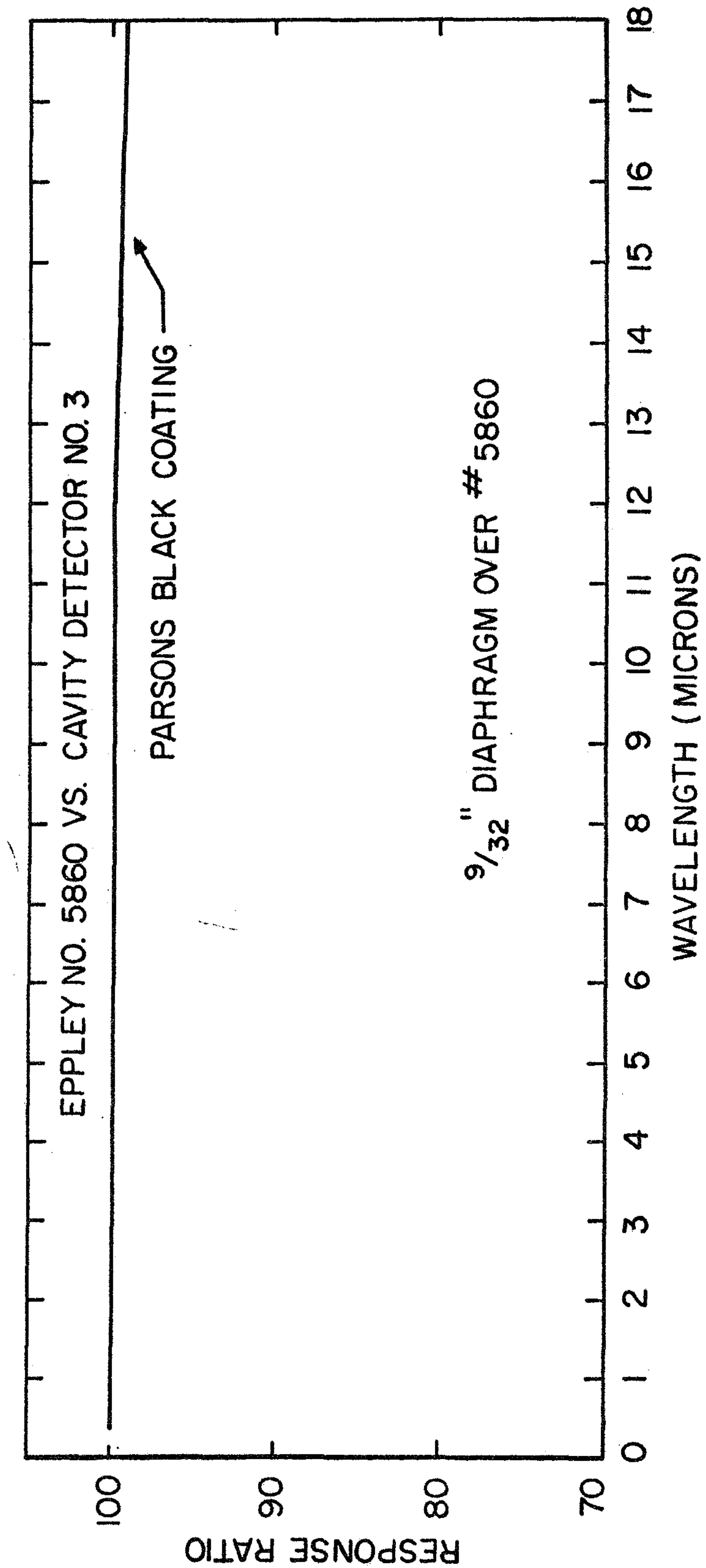

EPPLEY NO. 5860 VS. CAVITY DETECTOR NO. 3
PARSONS BLACK COATING
9/32" DIAPHRAGM OVER #5860
WAVELENGTH (MICRONS)
RESPONSE RATIO
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
100
90
80
70

Figure 6

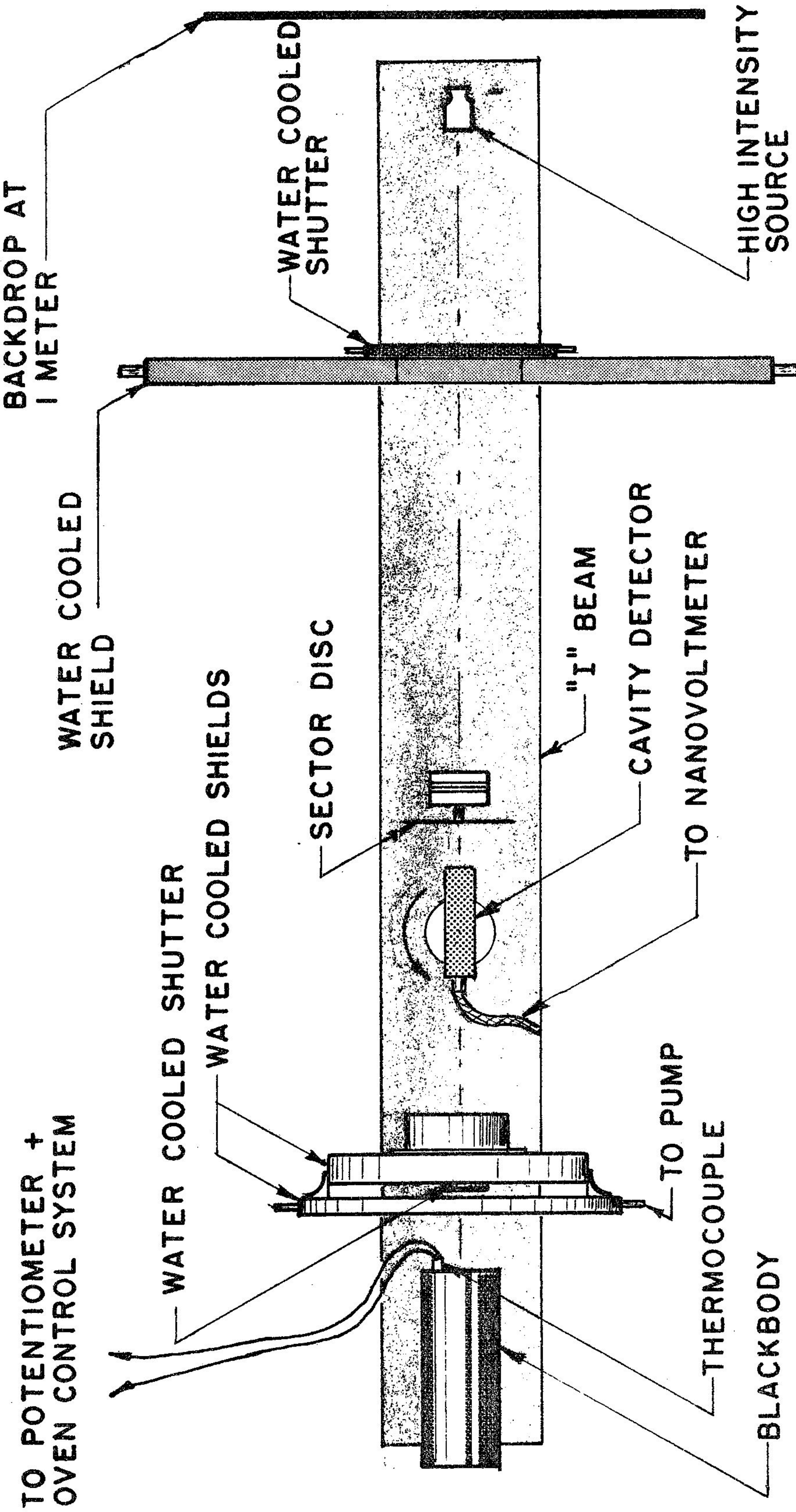

BACKDROP AT
I METER
WATER COOLED
SHUTTER
HIGH INTENSITY
SOURCE
TO PUMP
WATER COOLED
SHIELD
SECTOR DISC
"I" BEAM
CAVITY DETECTOR
TO NANOVOLTMETER
TO POTENTIOMETER +
OVEN CONTROL SYSTEM
WATER COOLED SHUTTER
WATER COOLED SHIELDS
TO PUMP
THERMOCOUPLE
BLACKBODY

Figure 7

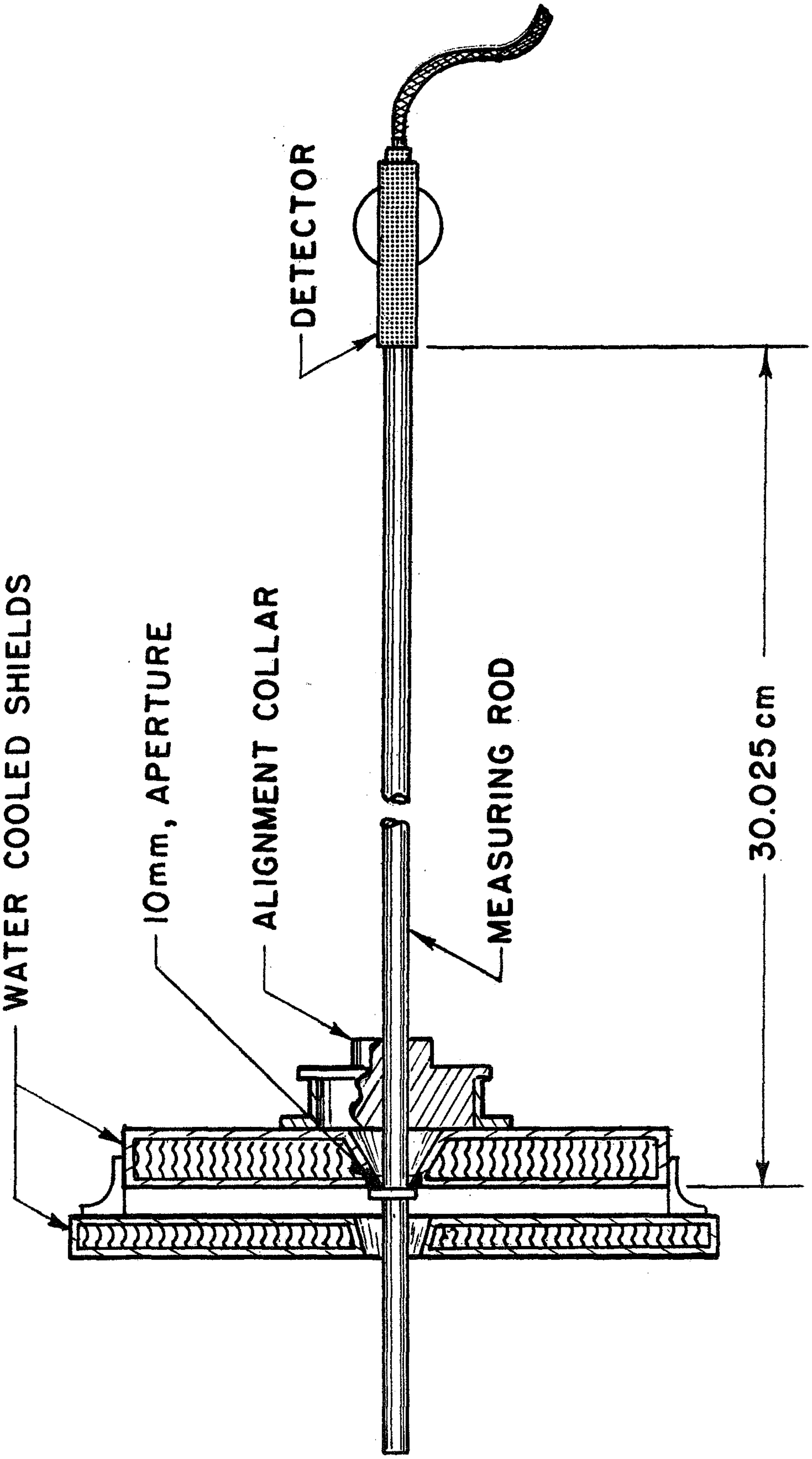

DETECTOR
WATER COOLED SHIELDS
10mm, APERTURE
ALIGNMENT COLLAR
MEASURING ROD
30.025 cm

Figure 8

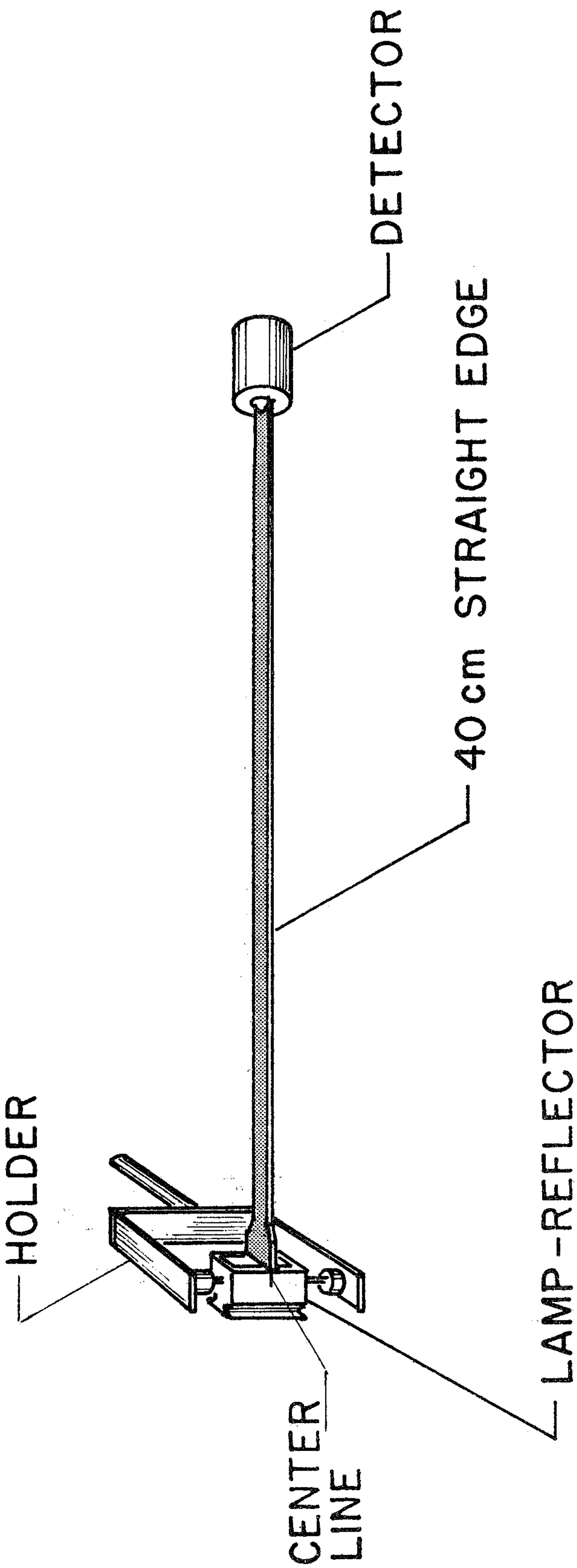

DETECTOR
40 cm STRAIGHT EDGE
HOLDER
LAMP-REFLECTOR
CENTER LINE

Figure 9

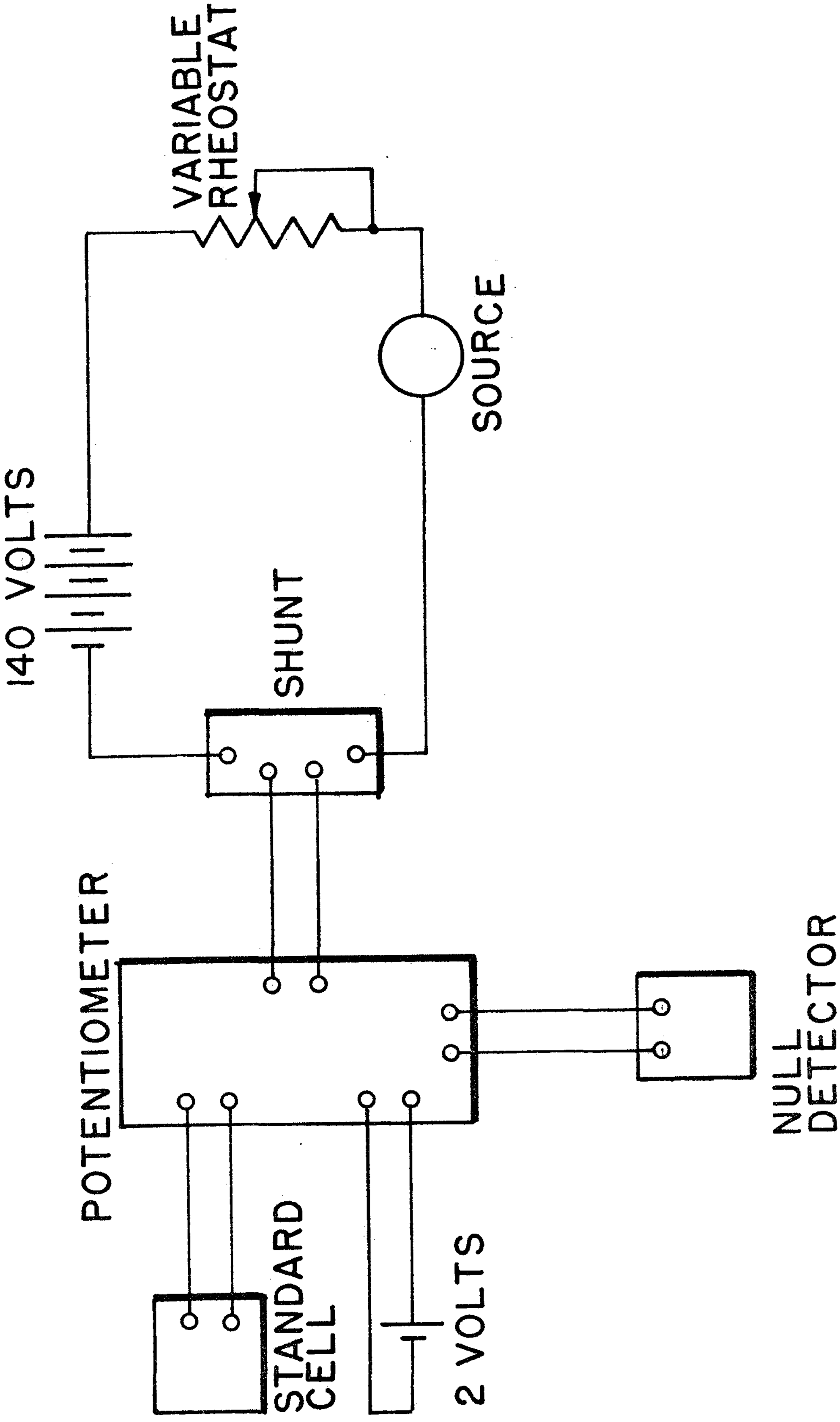

VARIABLE
RHEOSTAT
SOURCE
140 VOLTS
SHUNT
POTENTIOMETER
NULL
DETECTOR
STANDARD
CELL
2 VOLTS

Figure 10

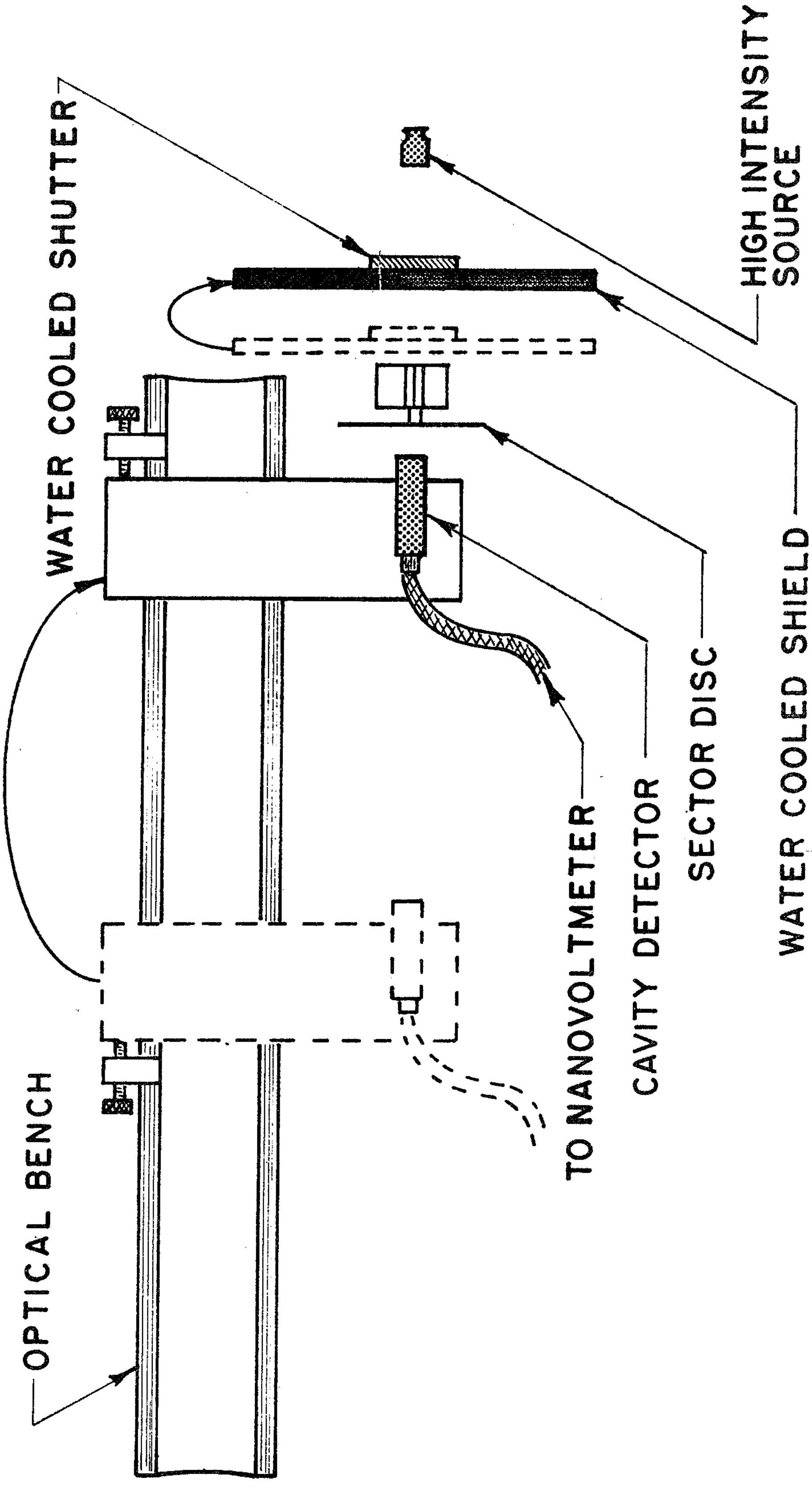

WATER COOLED SHUTTER
HIGH INTENSITY SOURCE
WATER COOLED SHIELD
SECTOR DISC
CAVITY DETECTOR
TO NANOVOLTMETER
OPTICAL BENCH

Figure 11

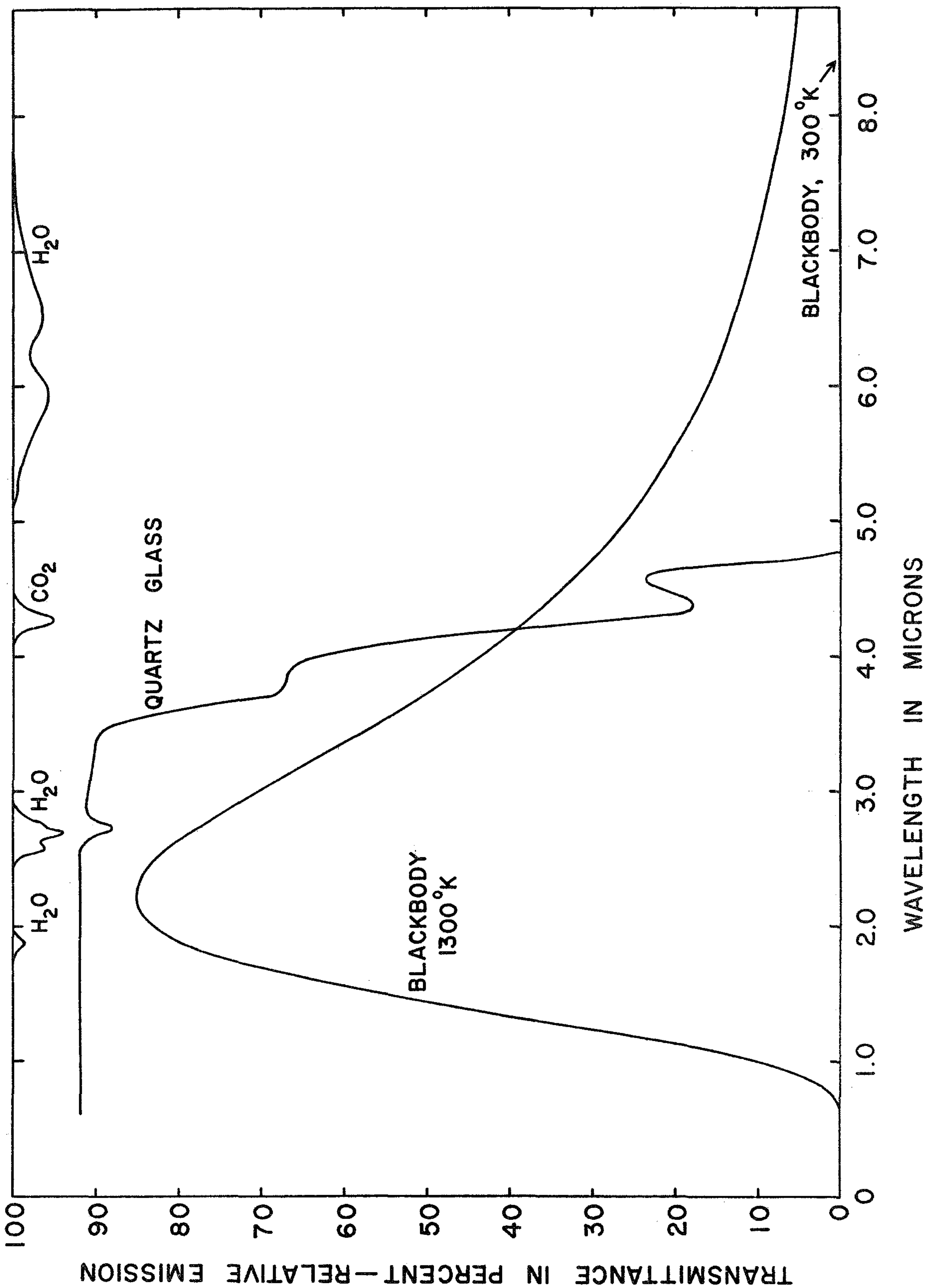

TRANSMITTANCE IN PERCENT—RELATIVE EMISSION
WAVELENGTH IN MICRONS
H_2O
H_2O
CO_2
H_2O
QUARTZ GLASS
BLACKBODY
1300°K
BLACKBODY, 300°K
0
10
20
30
40
50
60
70
80
90
100
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Figure 12

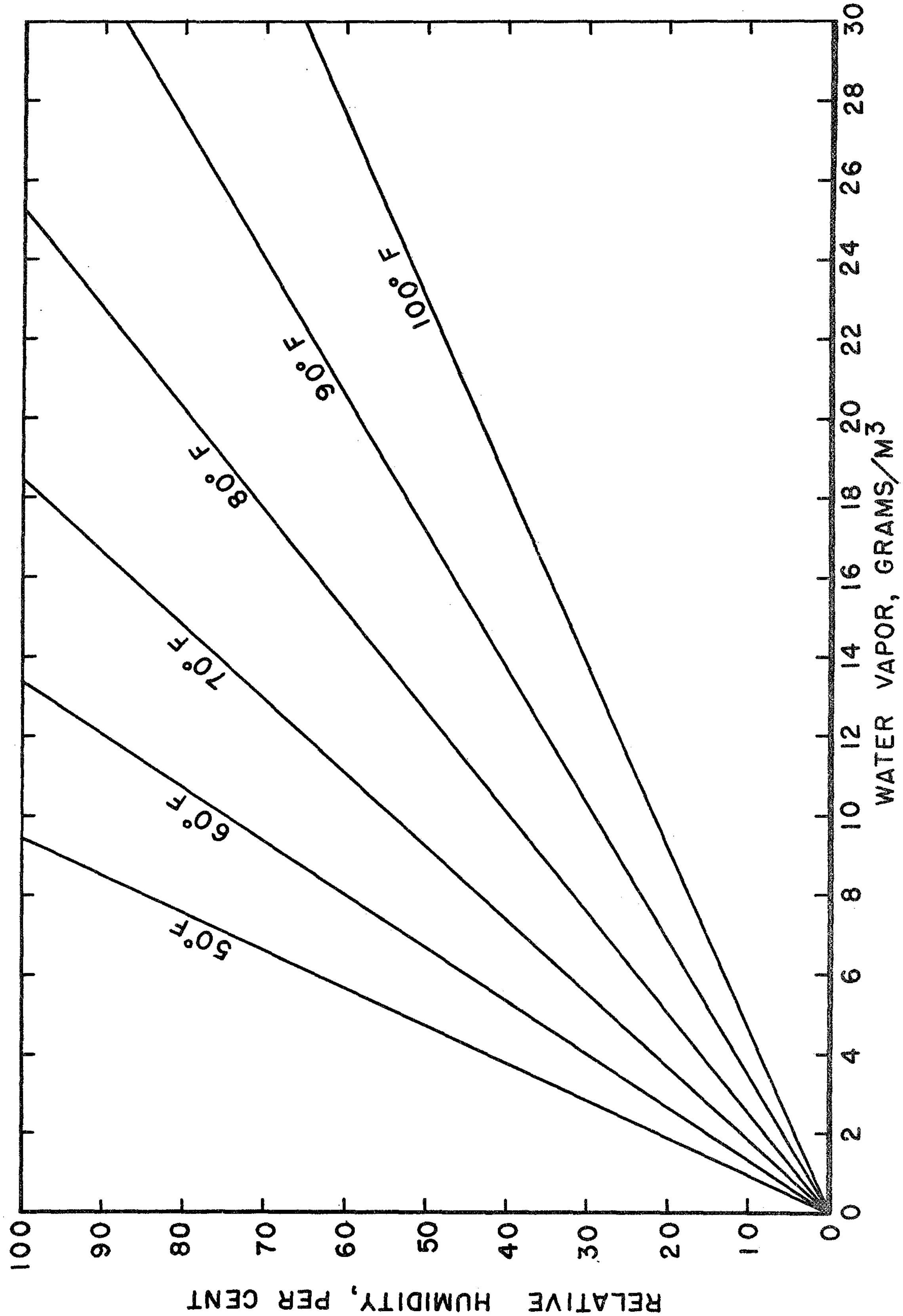

50°F
60°F
70°F
80°F
90°F
100°F
WATER VAPOR, GRAMS/M^3
RELATIVE HUMIDITY, PER CENT
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
10
20
30
40
50
60
70
80
90
100

Figure 13

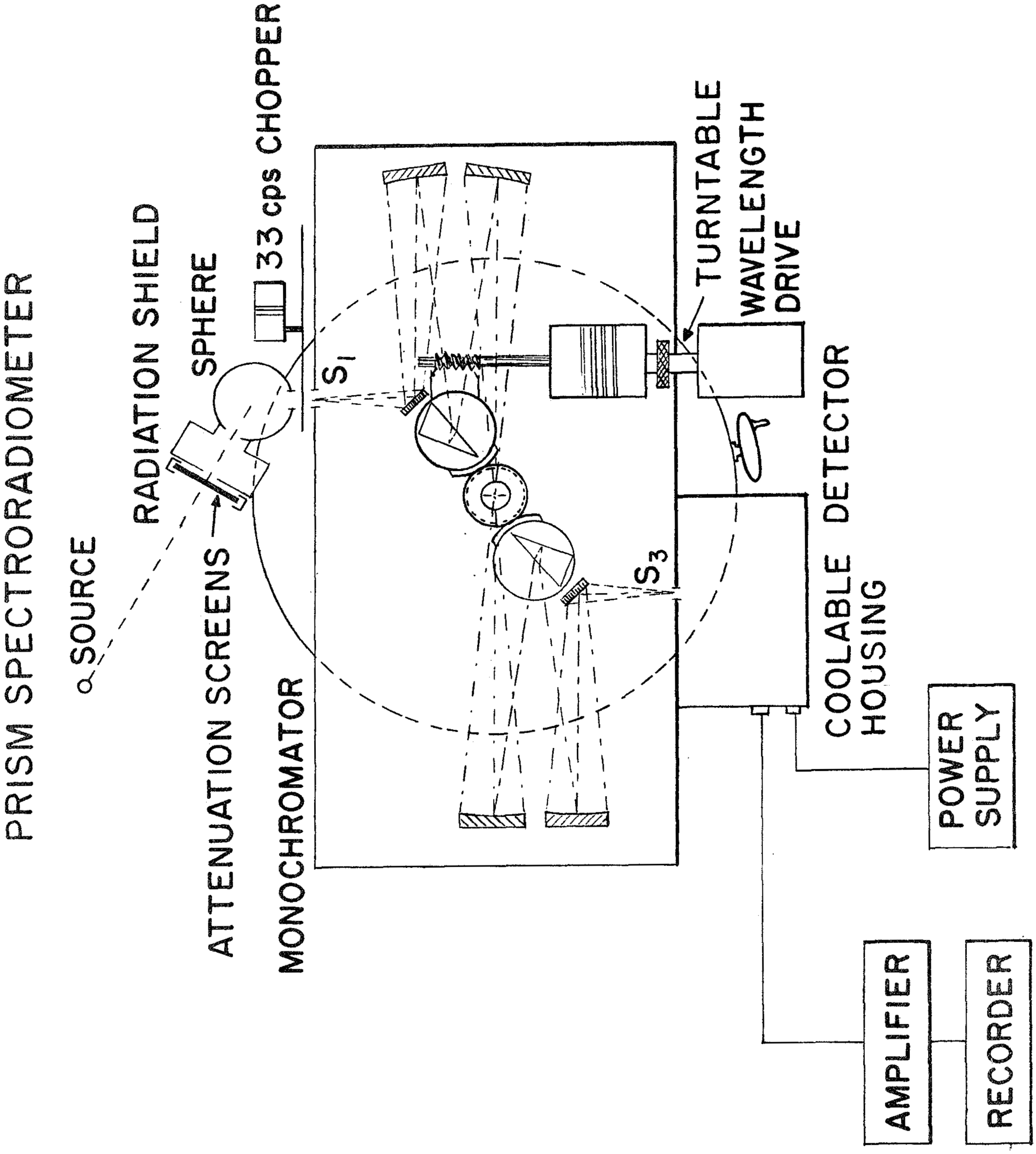

PRISM SPECTRORADIOMETER
SOURCE
RADIATION SHIELD
SPHERE
33 cps CHOPPER
ATTENUATION SCREENS
MONOCHROMATOR
S_1
S_3
TURNTABLE
WAVELENGTH
DRIVE
DETECTOR
COOLABLE
HOUSING
POWER
SUPPLY
AMPLIFIER
RECORDER

Figure 14

SPECTRAL IRRADIANCE OF 1000-WATT TUNGSTEN-HALOGEN LAMP ST-3 AT 50 cm. - - - - - - - - - -

SPECTRAL IRRADIANCE OF HIGH-INTENSITY UNIT T-3 AT 40 cm. ————————

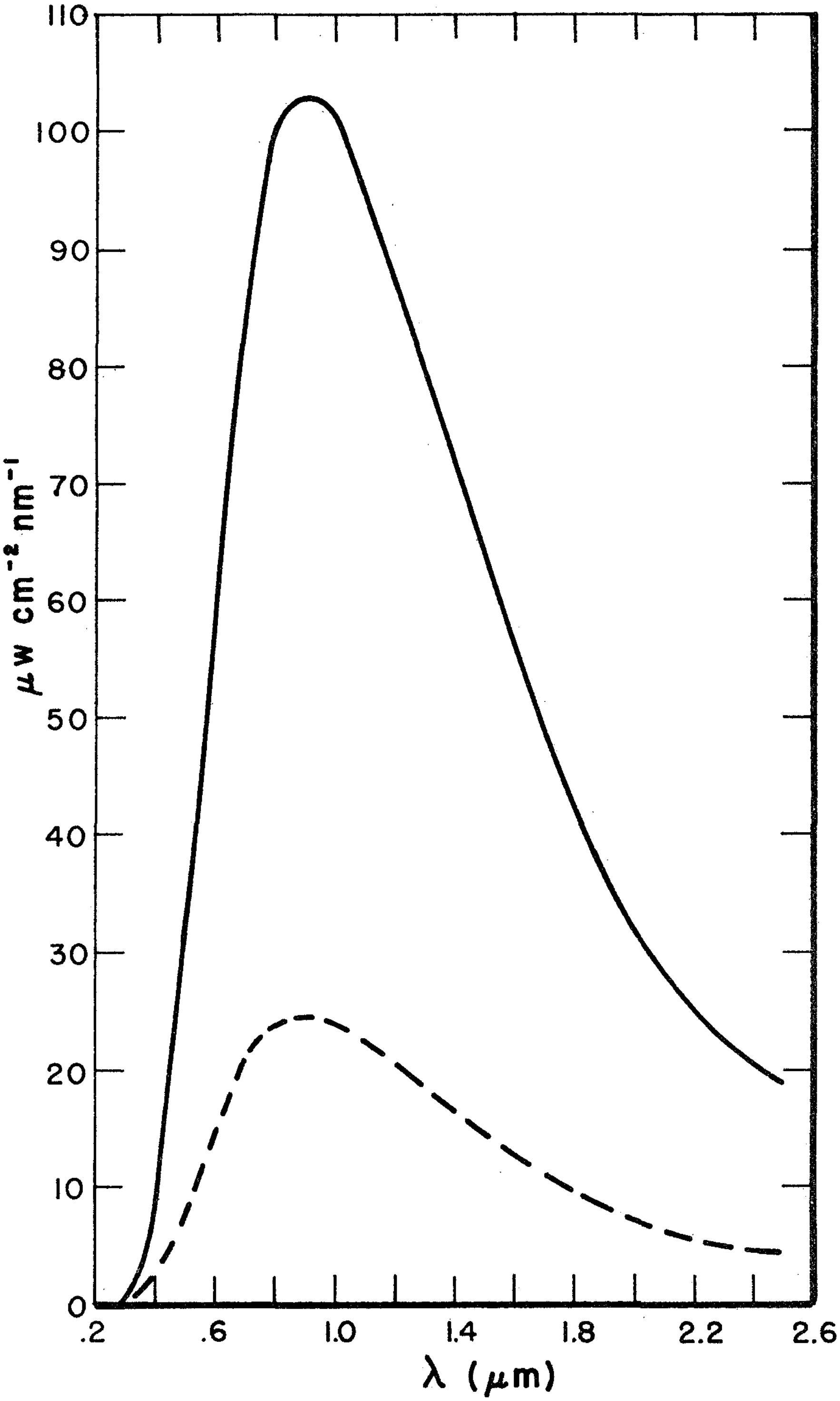


Figure 15

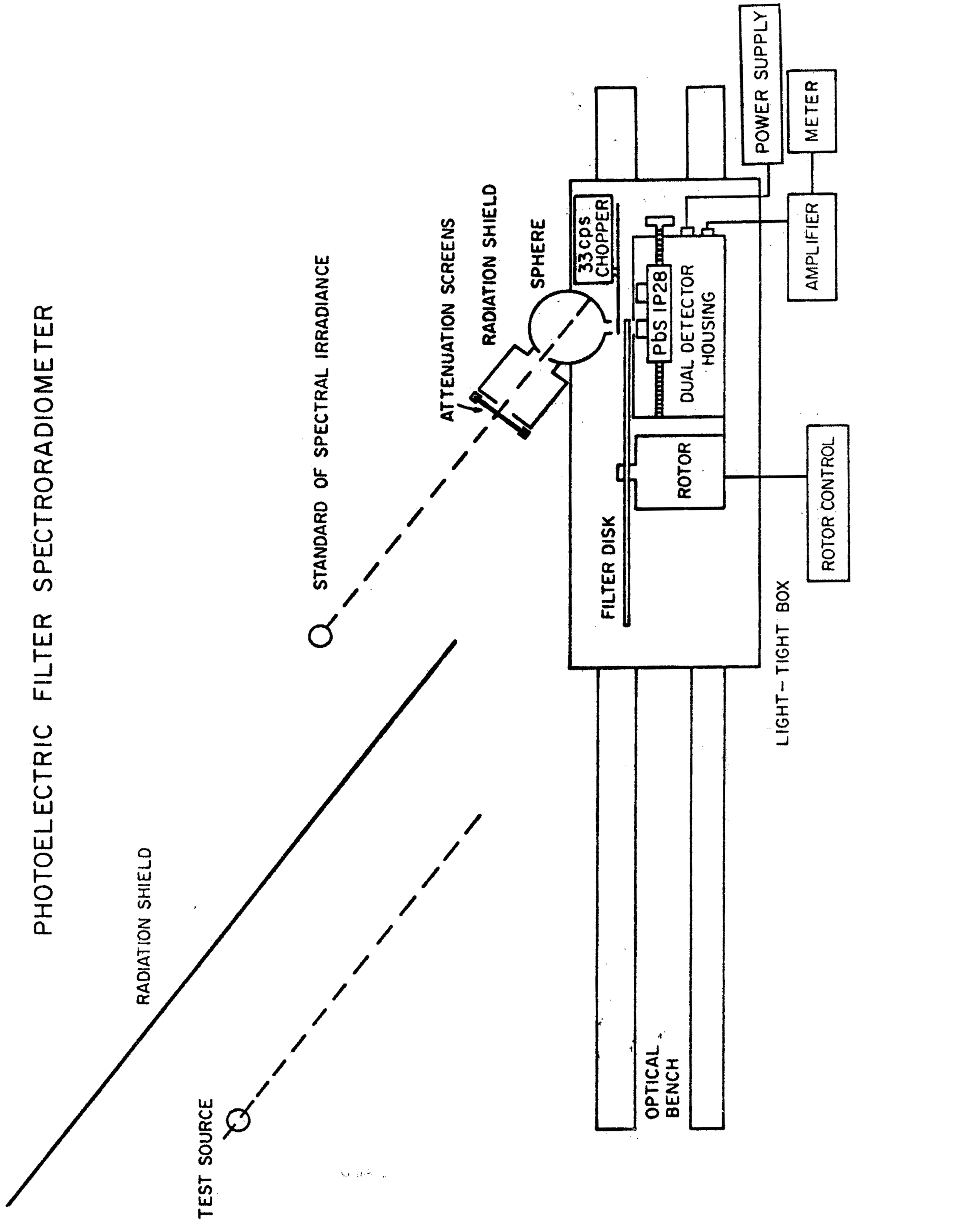

PHOTOELECTRIC FILTER SPECTRORADIOMETER
RADIATION SHIELD
TEST SOURCE
STANDARD OF SPECTRAL IRRADIANCE
ATTENUATION SCREENS
RADIATION SHIELD
SPHERE
33cps CHOPPER
PbS IP28
DUAL DETECTOR HOUSING
ROTOR
FILTER DISK
POWER SUPPLY
METER
AMPLIFIER
ROTOR CONTROL
LIGHT-TIGHT BOX
OPTICAL BENCH

Figure 16

COMPARISON OF PRISM AND FILTER SPECTRORADIOMETRIC MEASUREMENTS FOR HIGH-INTENSITY UNIT T-4

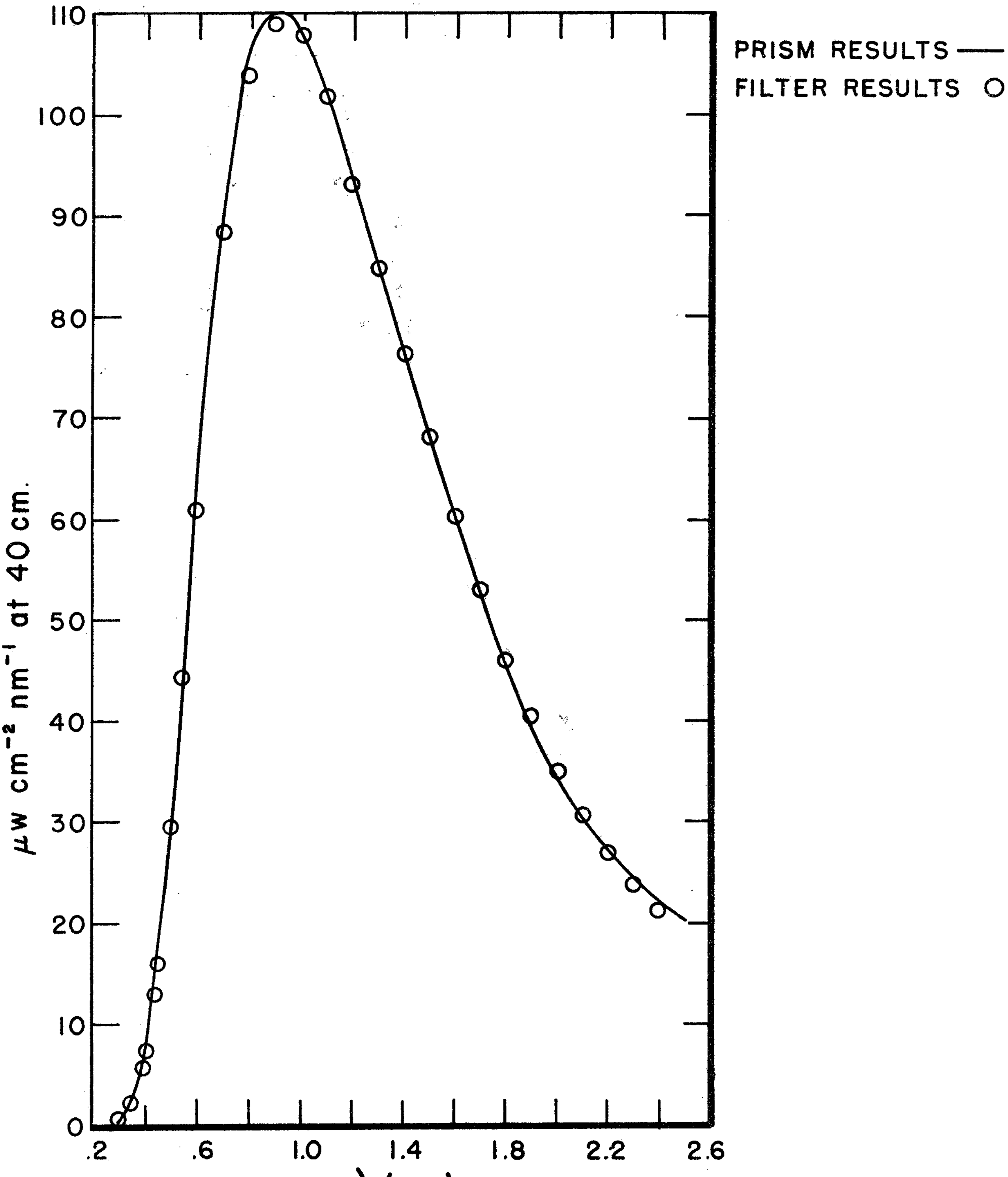


Figure 17

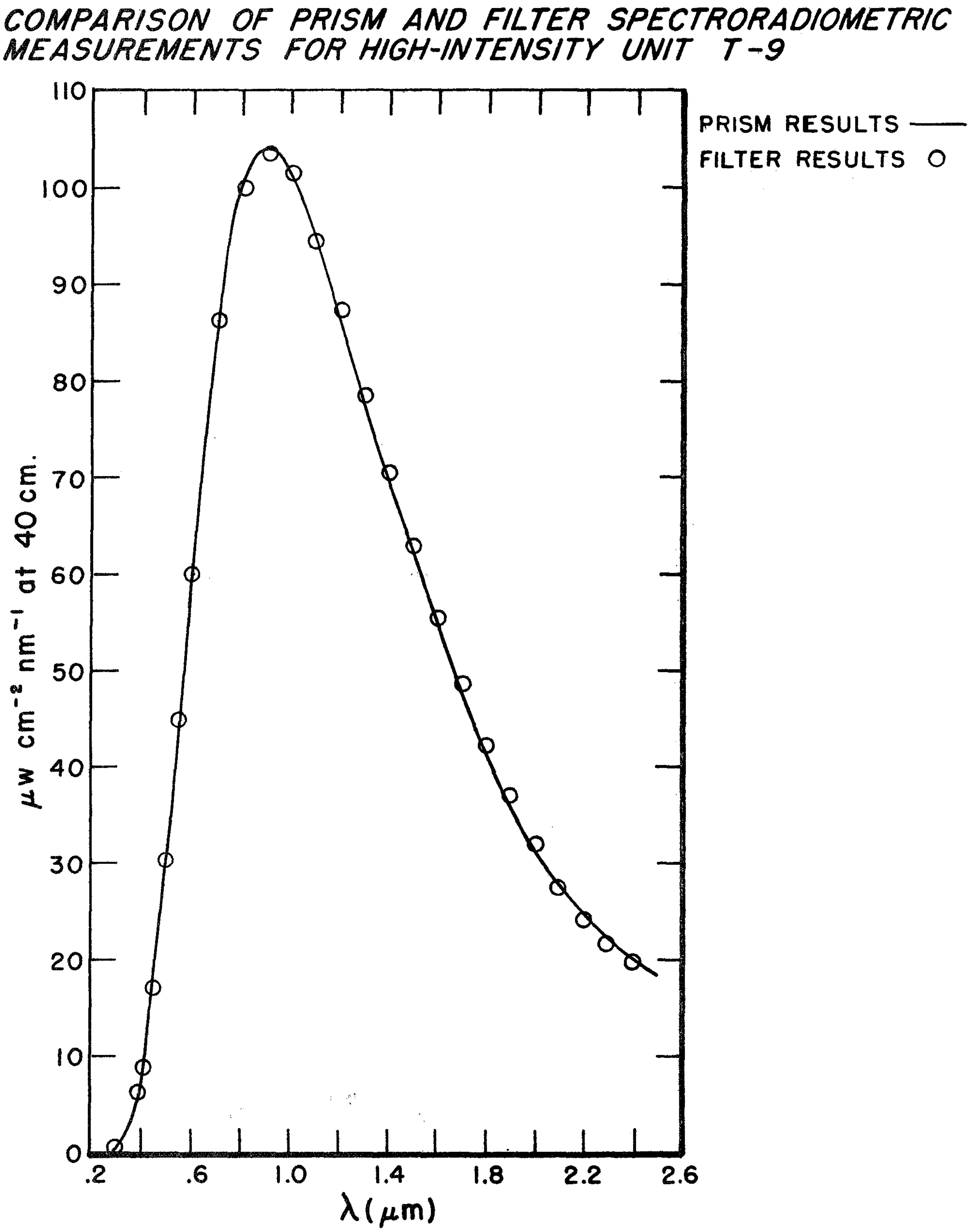
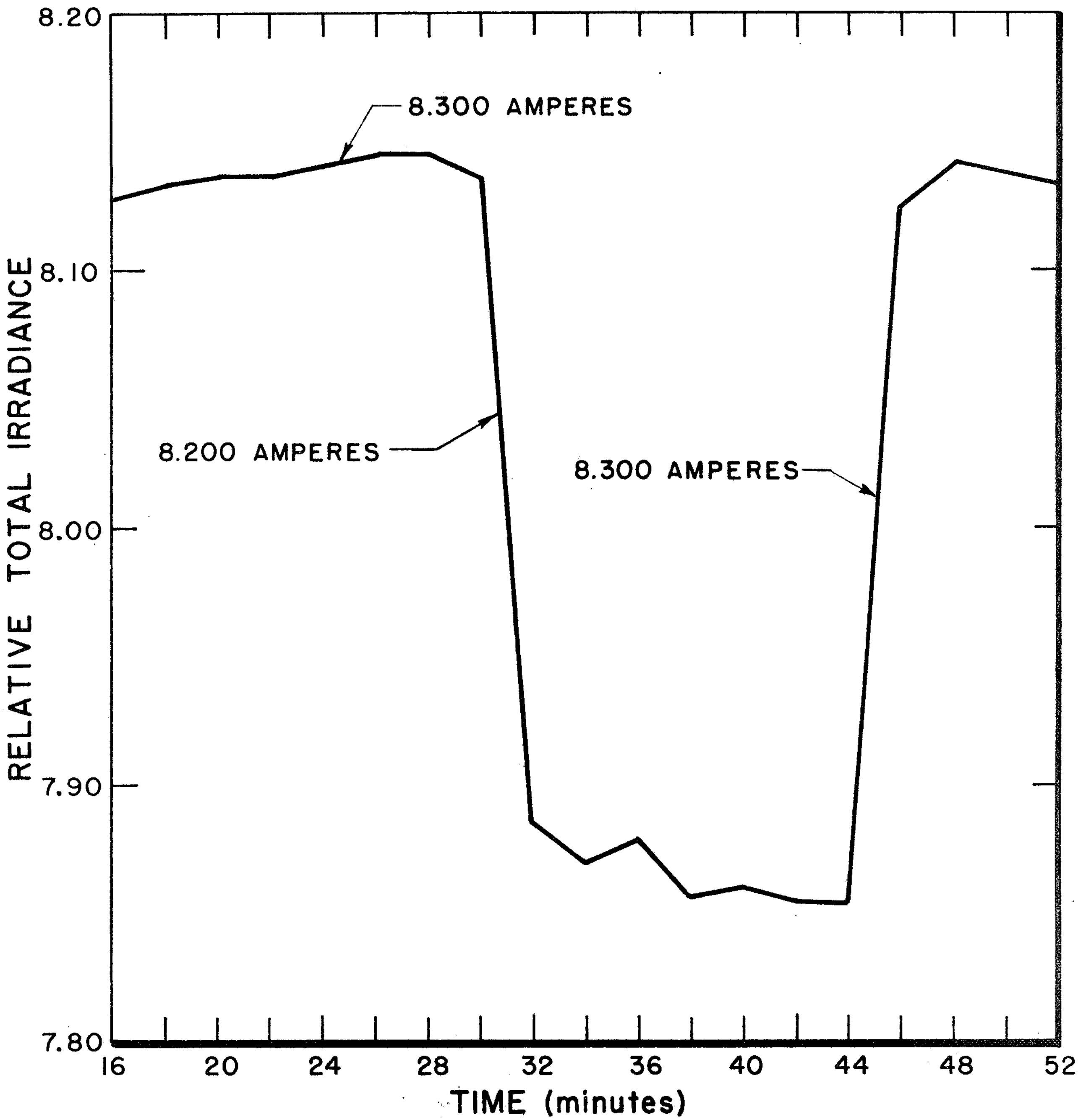

COMPARISON OF PRISM AND FILTER SPECTRORADIOMETRIC MEASUREMENTS FOR HIGH-INTENSITY UNIT T-9
PRISM RESULTS
FILTER RESULTS
μw cm⁻² nm⁻¹ at 40 cm.
λ (μm)
0
10
20
30
40
50
60
70
80
90
100
110
.2
.6
1.0
1.4
1.8
2.2
2.6

Figure 18



8.20
8.10
8.00
7.90
7.80
RELATIVE TOTAL IRRADIANCE
8.300 AMPERES
8.200 AMPERES
8.300 AMPERES
16
20
24
28
32
36
40
44
48
52
TIME (minutes)

Figure 19

Appendix A

Instructions for Using the High Intensity Standards of Total and Spectral Irradiance

These instructions cover the use of the high intensity standards of total and spectral irradiance. The standards consist of commercial G.E. 1000-watt type DXW or FBY tungsten halogen lamps mounted in ceramic reflectors. The reflectors are slip-cast fused silica and have a flame sprayed Al_2O_3 reflecting surface. The lamp-reflector combination results in a source capable of producing an irradiance at 40 cm. on the order of a solar constant (about 136 mw cm^{-2}). The effective size of the radiating source is about 3 cm. by 5 cm. Uniformity tests performed on a number of these units show that the irradiance in the specified direction over an area of 4 cm^2 is uniform to about $\pm$ 0.25%. Long term stability tests indicate that the total irradiance remains constant to about $\pm$ 0.3% for periods of about 50 hours. During this period, the ultra-violet irradiance has a tendency to gradually decrease by about 2 - 3 percent. This is due primarily to ultra-violet degradation of the Al_2O_3 coating.

The radiant intensity of the entire unit as mounted in the manner prescribed below is measured and reported. The total irradiances of the high intensity standards are based upon the total radiance of a blackbody as defined by the Stefan-Boltzmann equation. The assigned values have an uncertainty of about $\pm$ 1.0 percent. The values of the issued standards, compared to the reference standards, are in agreement to about 0.3 percent. The spectral irradiances are based on the radiance of a blackbody as governed by Planck's radiation law and have been determined through comparison with a group of 1000-watt quartz-iodine lamp standards of spectral irradiance. The uncertainty in the spectral values ranges from about 5 percent in the visible and infrared to about 8 percent in the ultra-violet.

Use of the Standards

The unit should be mounted in the supplied holder and aligned as shown in Figure A. The rear end and the side of the reflector having a scribed center line are both made vertical. Measurement of distance should be made from the front of the ceramic reflector. Thus, the unit is orientated in such a manner that an imaginary line from the detector (or object to be irradiated) to the source is normal to the front plane of the reflector.

For highest accuracy, the current through the lamp should be set at 8.30 amperes d.c. If the measurement of current is made when a voltmeter is in the circuit with the lamp, a correction will usually have to be made to the observed current. The setting of current through the lamp is, of course, sufficient to determine the irradiance of the source at the specified distance and direction; the voltage being useful mainly to determine whether the lamp characteristics have remained constant.

A black back-drop should be placed about 1 meter to the rear of the source. A water-cooled shield about 50 cm by 60 cm. with an opening 10 cm. in diameter should be positioned 25 cm. in front of the reflector. To screen the opening, a water-cooled shutter (15 cm. by 15 cm.) should be placed between the shield and the source. The shield and shutter should be painted black on all sides and be kept at a temperature of 25 ± 5°C.

Before the lamp is turned on, the shutter should be opened and closed to determine the amount of stray thermal radiation falling upon the radiometer. This test may be applied at any time provided the lamp has been given sufficient time to come to room temperature (about 15 minutes). The screen to the rear of the lamp may be cooler than the shutter, which will cause a negative deflection. The correction to the observed lamp deflection is, in that case, positive. It is desirable to make the calibration in a dimly lighted room to avoid errors from sunlight which is continually varying with cloudiness, thus varying stray radiant energy within the room as well as the temperature of the screens and also causing air currents near the radiometer. The insertion of diaphragms between the shutter and the radiation detector may be helpful in minimizing this background energy.

These standards require no auxiliary optics. If any are employed proper correction must be made for their optical characteristics. The lamp is simply placed at a measured distance from the detector or spectrometer slit.

Values of spectral irradiance for these lamps are tabulated as a function of wavelength in microwatts per (square centimeter-nanometer) at a distance of 40 centimeters from front of reflector to receiver. Values of spectral irradiance for wavelength intervals other than one nanometer, say x nanometers, may be found by multiplying the tabulated values by x.

These standards of irradiance are expensive laboratory equipment and it is suggested that they be operated sparingly and with care in order to prolong their useful life. They should be turned on and off at reduced current, and great care should be taken so that at no time will the current appreciably exceed 8.30 amperes. It is recommended that for general use, working standards be prepared by calibrating them relative to the laboratory standard supplied by NBS.

These lamps operate at high temperatures such that the quartz envelope is above the flammable point of organic materials. They may thus cause fires, and also the burning of lint, etc. on the envelope which may result in optical damage to its surface. At no time should the fingers come into contact with the quartz envelope, or the Al_2O_3 reflecting surface.

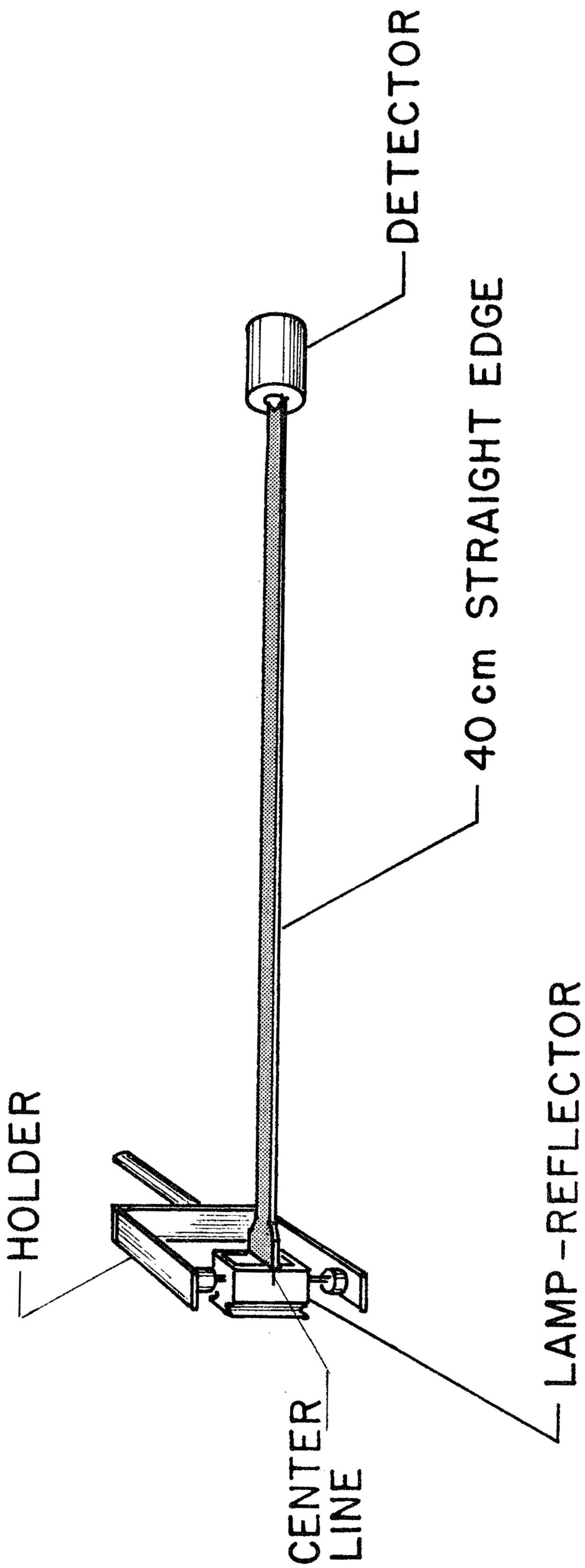

DETECTOR
40 cm STRAIGHT EDGE
LAMP-REFLECTOR
HOLDER
CENTER
LINE

Figure A

Appendix B

Fabrication of Reflectors

The reflectors were supplied by Pyro-Metric, Inc., Seattle, Washington. They consist of slip-cast fused silica; a material possessing low conductivity, high reflectivity, and minimal thermal shock and expansion at temperatures from near 273°K to the melting point (about 2000°K).

In the fabrication of the reflectors, it is necessary to first make a pattern of the desired configuration, a muster mold, and a casting mold. Calculations for shrinkage and expansion must be allowed for in the various materials used. When the mold is ready, the liquid fused silica material is poured into it to form what is called a "green ware". Further shaping and sanding is necessary to provide for close tolerances. A firing procedure is then followed which permits the material to dry gradually prior to the application of a high temperature firing cycle. After the fused silica has been fired, it acquires a bright whiteness which possesses excellent reflective characteristics. It does not burn or tarnish and maintains its white color at high temperatures. Tungsten-halogen lamps, with the end seals encapsulated to prevent oxidation and deterioration from the heat of the lamp, are sealed into the reflector.

Appendix C

Two Solar Constant Source

The feasibility of developing a source capable of producing an irradiance of roughly two solar constants (about 272 mw cm^{-2}) was also considered. Ceramic reflectors were designed such that two 1000-watt tungsten-halogen lamps could be mounted side by side in the reflector. Thus, this source should have an irradiance roughly twice that of the single lamp-reflector combination.

Stability tests on the double lamp-reflector units were conducted in the same manner as with the single units. The two lamps were wired in series and operated at a current of 8.20 amperes. Initial tests were encouraging in that the units operated about 50 hours before failure. The results of a stability test on one of these units is given in Table A. Note that the total irradiance decreases by about 2% over the 50-hour period and the ultra-violet decreases by about 9 percent. The reflectors were accordingly redesigned a number of times in an attempt to increase the life of the lamps, both clear and frosted lamps were sealed in the reflectors. However, the frosted lamps usually failed in less than 20 hours.

Table A

Relative Spectral and Total Irradiance Ratios for Two Clear 1000-Watt Lamps in an Al_2O_3 Coated Reflector at about 200 cm. VS. a 1000-Watt Reference Source at 75 cm. as a Function of Time

Time (hrs.)	3	12	19	25	34	42	50
λ (μm)							
.2537	.653	.633	.626	.626	.603	.612	.601
.300	.708	.687	.670	.671	.660	.663	.652
.500	1.23	1.22	1.20	1.20	1.19	1.20	1.17
.700	1.31	1.31	1.31	1.32	1.30	1.30	1.29
1.0	1.33	1.32	1.33	1.33	1.31	1.33	1.31
1.5	1.34	1.35	1.35	1.36	1.34	1.36	1.33
2.0	1.36	1.37	1.37	1.38	1.37	1.37	1.36
TOTAL	1.312	1.305	1.289	1.290	1.290	1.290	1.286

Appendix D

1000-Watt Standards of Total and Spectral Irradiance

Since the experimental apparatus for making irradiance measurements was set up, a group of clear and frosted 1000-watt lamps (without reflectors) were calibrated in terms of total and spectral irradiance. The total measurements were made relative to the 1400°K blackbody with the lamps positioned at 50 and 100 cm. from the detector. The spectral irradiances were determined at 50 cm. through direct comparison with the NBS 1000-watt standards of spectral irradiance.

For the total measurements, the 5 and 30 percent transmitting sector disks were used. A minimum of five calibrations was made for each of the lamps. As with the high-intensity units, the repeatability in terms of a standard deviation was $\pm$ 0.3%. The results of the measurements are given in Table B.

The spectral comparisons were made over the wavelength interval of 0.25 to 2.5 μm using the prism spectroradiometer. Each lamp was compared to at least three standards of spectral irradiance. The results of these measurements are given in Table C.

Table B

Total Irradiance of 1000-Watt Tungsten-Halogen Lamps in mw cm^{-2}

Unit No.	Total Irradiance
ST-1	32.39
ST-2	32.63
ST-3	31.87
ST-6	32.78
ST-7	33.83
ST-8	32.98

Table C

Spectral Irradiance of 1000-Watt Tungsten-Halogen Lamps in μw cm^{-2}-nm^{-1}

at 50 cm. when Operated at 8.30 Amperes

λ(μm)	ST-1	ST-2	ST-3	ST-6	ST-7	ST-8
.250	.0202	.0221	.0194	.0165	.0167	.0156
.260	.0359	.0391	.0345	.0308	.0310	.0292
.270	.0604	.0645	.0584	.0535	.0542	.0512
.280	.0962	.104	.0933	.0874	.0890	.0836
.290	.145	.156	.141	.134	.137	.128
.300	.208	.222	.202	.195	.199	.186
.320	.392	.419	.381	.376	.386	.360
.350	.891	.947	.869	.873	.902	.840
.370	1.36	1.45	1.33	1.35	1.39	1.30
.400	2.37	2.51	2.32	2.37	2.44	2.29
.450	4.68	4.89	4.55	4.70	4.85	4.61
.500	7.82	8.12	7.65	7.93	8.17	7.86
.550	11.3	11.6	11.0	11.4	11.8	11.4
.600	14.8	15.1	14.4	14.9	15.5	15.0
.650	18.1	18.5	17.7	18.3	19.0	18.4
.700	20.9	21.4	20.5	21.3	22.0	21.4
.750	22.9	23.3	22.4	23.3	24.1	23.4
.800	24.1	24.4	23.6	24.5	25.3	24.7
.9	24.9	25.1	24.4	25.3	26.0	25.5
1.0	24.3	24.5	23.8	24.6	25.2	24.8
1.1	22.7	22.9	22.4	22.9	23.5	23.2
1.2	20.8	20.9	20.5	20.9	21.4	21.2
1.3	18.7	18.8	18.5	18.9	19.3	19.2
1.4	16.7	16.8	16.5	16.9	17.3	17.2
1.5	14.8	14.9	14.6	15.0	15.3	15.2
1.6	13.0	13.1	12.8	13.2	13.5	13.4
1.7	11.3	11.4	11.2	11.5	11.8	11.7
1.8	9.84	9.88	9.75	9.97	10.2	10.2
1.9	8.52	8.56	8.45	8.62	8.79	8.77
2.0	7.36	7.40	7.31	7.44	7.58	7.56
2.1	6.44	6.46	6.38	6.48	6.61	6.59
2.2	5.68	5.70	5.63	5.71	5.82	5.80
2.3	5.07	5.09	5.03	5.10	5.19	5.17
2.4	4.58	4.60	4.54	4.61	4.69	4.67
2.5	4.18	4.20	4.15	4.22	4.29	4.27